M thod and Apparatus for Waf r M trol gy

Inventors:

Fred E. Stanke, Clinton B. Carlisle, Hung Pham, Edric Tong, Robert Hamstra, Doulas E. Ruth, James Cahill, Michael Weber, Elliot Burke

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to the field of optical metrology, and in particular to in-line thin-film reflectometry and profilometry for semiconductor wafers.

Description of the Related Art

Within the integrated circuit (IC) industry, the trend toward smaller critical dimension sizes drives advances in technology for the capital equipment used in wafer fabrication. Both technical factors, such as the ratio of the critical dimension size to the wavelengths of light used in fabrication devices, as well as economic factors, such as wafer throughput, Cost-Of-Ownership (COO) and Overall Equipment Effectiveness (OEE), are critical.

In IC fabrication, hundreds of process steps are necessary. During some of these process steps, successive layers of materials are placed on a substrate. Often, a film layer deposited on the wafer during a previous process step is subsequently planarized to high degree of precision. This planarization is often accomplished by Chemical Mechanical Polishing (CMP). After a CMP process step, the thickness of the remaining film may be determined to verify that it is within tolerances.

Optical methods are convenient to determine the thickness of thin films since light is generally non-destructive and non-invasive. Measured optical properties of the surface or measured wave-optics effects due to the interaction of light with thin films yield desired information about the films residing on the wafer. As critical dimensions on the wafer are reduced, optical metrology techniques must be advanced to obtain required precision and accuracy.

Economic factors also drive technology development for semi-conductor capital equipment. Machines must process wafers at a rapid rate with high uniformity, high precision, and high reliability. Since the fabrication must take place in a strictly controlled environment, the size of the machine is also an important factor. Easy operation is also highly important, despite the complexity of the processing and measurements. Performance in terms of these and other economic factors can be expressed through figures-of-merit such as COO and OEE.

In the 1990's, IC manufacturers have focused on economic factors such as OEE, COO and yield improvement. A fundamental need is to accurately measure geometry, topology, and contamination of the wafer during processing. Addressing this need has resulted in the use of "metrology mainframe" devices, which are devices only partially integrated with the IC fabrication line.

Despite being "off-line," the results achieved by such process control devices have been outstanding. Currently, yields on advanced IC production are as high as 80~90%, compared to 50~60% or less a decade earlier. However, the cost of fabrication equipment capable of these greater yields has increased by a factor of 3-5.

Two major problems associated with off-line metrology control methods are:

(1) waiting for test measurements from metrology mainframe systems to confirm the results from each process step; and

(2) difficulties faced by process engineers in achieving and maintaining optimal process parameters.

In the future, integrated (in-line) metrology, in which metrology devices are physically placed within the process equipment itself, will become necessary to meet cost reduction requirements.

The integrated metrology approach consists of integrating a metrology system into the process tool, enabling a substantial reduction in times required to perform metrological measurements and shortening feedback times between the metrology system and the process controls. By measuring critical parameters as each wafer is processed, the process tool has information on the most recent wafer without stopping production. This results in good wafer-to-wafer control. The integrated metrology approach also significantly reduces operating costs by reducing the requirement for expensive test wafers, speeding up process qualifications and maintenance schedules, and provides an overall reduction in scrap

wafers. From the above, it can be appreciated that many processes used in microelectronics manufacturing could benefit from integrated metrology, including CMP, plasma etch, chemical vapor deposition, and lithograpghy processes.

Prior art commercial devices for integrated thin-film metrology are limited regarding combining the ability to precisely and accurately measure thin-film thickness while meeting the other industry requirements. Typically, prior art in-line devices are limited to measurements of films of about 80 nanometers thickness. However, there is a need in the industry to measure film thickness of only a few tens of nanometers. Further, prior art devices are limited in their ability to make rapid, successive measurements over the totality of a wafer's surface. Therefore, there is a need within the semiconductor industry for improved apparatae and methods for integrated thin-film metrology offering significant advantages over limitations of the prior art.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows an overview of the system hardware for a particular embodiment.

FIG. 2A and FIG. 2B show a novel aspect of a particular embodiment.

FIG. 3 shows an exemplary reference reflector embodiment.

FIG. 4 shows an exemplary embodiment of the wafer aligner.

FIG. 5 illustrates calibration of the wafer aligner.

FIG. 6 shows another aspect of the invention that improves the accuracy of wafer alignment.

FIG. 7 illustrates the use of a large Field-Of-View (LFOV) camera and a small Field-Of-View (SFOV) camera to avoid groping in the process of locating a particular region of a wafer.

FIG. 8 illustrates the advantage of using of the LFOV camera to enable easy die size determination during training.

FIG. 9 shows a specular auto-focus system.

FIG. 10 illustrates an asymmetric specular auto-focus system.

FIG. 11 illustrates the sensitivity to tilt of an asymmetric specular auto-focus method.

FIG. 12 shows a particular embodiment of the auto-focus system.

FIG. 13 illustrates the increased sensitivity to surface displacement obtained by utilizing symmetrical specular auto-focus.

FIG. 14 shows the insensitivity to surface tilt of the symmetric specular auto-focus system.

FIG. 15 shows an alternate embodiment of the auto-focus system.

FIG. 16 illustrates the insensitivity to surface tilt of the embodiment shown in FIG. 15.

FIG. 17 illustrates a wafer support embodiment.

FIG. 18 illustrates a wafer support embodiment.

FIG. 19 illustrates a wafer support embodiment.

FIG. 20 illustrates a wafer support embodiment.

FIG. 21 illustrates detail of a wafer support embodiment.

FIG. 22 illustrates detail of a wafer support embodiment.

FIG. 23 illustrates an embodiment of wafer immersion hardware prior to wafer immersion.

FIG. 24 illustrates an embodiment of wafer immersion hardware at an initial stage of wafer immersion.

FIG. 25 illustrates an embodiment of wafer immersion hardware at a late stage of wafer immersion.

FIG. 26 illustrates rotation of the wafer in the rotary wafer chuck.

DETAILED DESCRIPTION

FIG. 1 shows an overview of the system hardware for a particular embodiment of this invention. In FIG. 1, reflectometer assembly 100, vacuum chuck 101, vacuum chuck symmetry axis 102, light source fiber 103, first beam splitter 104, second beam splitter 105, semiconductor wafer 110, measurement region 111, window 120, collimator 130, relay optics 135, first imaging optical assembly 137, second imaging optical assembly 138, third imaging optical assembly 139, spectrographs (including calibration filters) 140 and 141, spectrograph fiber optic 145, pinhole mirrors 146, large field-of-view camera 150, small field-of-view camera 160, auto-focussing objective lens assembly 190, first optics breadboard 195, and second optics breadboard 197 are shown.

Semiconductor wafer 110 is coupled to vacuum chuck 101, whose center-of-mass is fixed relative to the laboratory and the semiconductor wafer coupled to it. However, rotation of the vacuum chuck about the vacuum chuck symmetry axis 102 is allowed. Reflectometer assembly 100 comprises window 120 and first and second optics breadboards 195 and 197, respectively. First optics breadboard 195 is free to translate along the y axis, and may be driven by a direct-drive actuator in a particular embodiment. Second optics breadboard 197 is coupled to the first optics breadboard, however, the second optics breadboard is free to translate relative to the first optics breadboard along the x axis. Objective lens assembly 190 is attached to the second optics breadboard, however, it is free to translate along the z axis. Thus, the embodiment shown in FIG. 1 has four degrees of freedom of movement: translation along the (x,y,z) axes; and rotation of the vacuum chuck about the vacuum chuck symmetry axis.

In the embodiment shown in FIG. 1, all optical elements except those on second optics breadboard 197 are coupled to and fixed relative to first optics breadboard 195. Objective lens assembly 190, are coupled to second optics breadboard 197. Thus, the objective lens assembly is free to translate along the x axis. In addition, the objective lens assembly may be focussed on semiconductor wafer 110 by translation along the z axis. Note that translations of the first and second optics breadboards along the x and y axes allows access to the full wafer surface. Rotation of the wafer coupled to the vacuum chuck may be used in combination with translations of the first and second optics breadboards along the x and y axes to allow more rapid measurement access over the entire surface of the semiconductor wafer or to eliminate obstructions. Complete coverage

of a 200 mm diameter wafer is possible with straightforward scaling to 300 mm and larger diameter wafers.

Reflectometer assembly 100 takes measurements from selected regions of semiconductor wafer 110. To locate a particular region of the semiconductor wafer for measurement, a surface of the semiconductor wafer is imaged by large field-of-view camera 150, and small field-of-view camera 160. The large field-of-view camera has an approximately 20 mm x 27 mm field-of-view. The small field-of view camera has an approximately 1 mm x 1.3 mm field-of-view.

Reflectometer assembly 100 comprises a broadband (UV, visible, NIR) reflectometer measurement system. In a particular embodiment, the light source (not shown) may be a Xenon lamp fiber-coupled to the system via source fiber 103. Relay optics 135 transfer collimated light from lens assembly 130 to beam splitter 104. The light transmitted directly through the beam splitter from the source fiber is referred to as the monitor beam. The monitor beam does not interact with the measurement region 111. The portion of the illumination that the beam splitter directs toward the wafer is referred to as the measurement beam. The measurement beam reflects from the surface of the wafer, where its spectrum is modified by the presence of thin films on the wafer.

Following reflection, the measurement beam returns to the beam splitter, and passes to several relay mirrors 135. First imaging optical assembly 137 focuses the measurement beam onto pinhole mirror 146. The light falling on a pin hole aperture in the pin-hole mirror passes into spectrograph fiber 145, which conveys it to spectrograph 140. The resulting spectrum is primary source of information about the films on the wafer.

The monitor beam follows a similar but distinct path through another pinhole mirror 146 and spectrograph fiber 145 to spectrograph 141. The measured monitor spectrum is indicative of the illumination system and optical components, and may be used to correct the measurement of film properties for instrument characteristics. A portion of the measurement beam reflected by pinhole mirror 146 is refocused onto small field-of-view (SFOV) camera 160. The resulting image is indicative of patterns on semiconductor wafer 110. The pinhole itself is also imaged onto the SFOV as a dark spot superimposed on the image of the wafer's patterns. This dark spot indicates the precise location where the thickness measurement is made with respect to the patterns on the wafer.

As described, the relative spectral content of both the incident and reflected light from semiconductor wafer 110 is measured. The thickness

of thin-films deposited on the measurement region 110 can then be determined from the reflected "measurement beam" and incident "monitor beam" light by wave-optics principles well-known in the art.

An advantage of the invention over the prior art is scanning with relay mirrors is employed in only one spatial dimension. If the light beams reflected from the relay mirrors were perfectly collimated and aligned, scanning would have no deleterious effects on the performance of the system. However, due to diffraction, the beams cannot be perfectly collimated and perfect alignment is unattainable in practice. Therefore, it would be preferable to scan the object with respect to the optics as little as possible. In the current invention, the majority of the optics scan in one dimension on the first optics breadboard, and the rest of the optics scan in two dimensions with respect to a laboratory-fixed coordinate system, but only one dimension (X) with respect to the first optics breadboard. Thus, the relay scan length is no more than one wafer diameter. In prior art devices, the optics are fixed, and the objective scans in two dimensions, requiring a scan length of up to two wafer diameters.

A further advantage of the invention over the prior art is that the optical path length remains constant, regardless of scan position. Thus, if the object is treated as a focal point, with a specular reflection from the surface of the wafer, the amount of diffraction in the beam does not change. In prior art devices, spatial scanning over a wafer surface changes the total optical path length, and thus the amount of diffraction suffered by a collimated beam.

It is noteworthy that in the embodiment shown in FIG. 1, semiconductor wafer 110 is located above reflectometer assembly 100. In alternative embodiments, the semiconductor wafer may be held in a pool of water below the optical system, which may be configured to 'look' down instead of up. This would necessitate differences from FIG. 1 in the handling of the wafer, which would have its device side up. In such alternate embodiments, either the optical system (including a main window) may be lowered toward the semiconductor wafer or the semiconductor wafer may be raised toward the optical system. Such an alternate embodiment would be a 180 degrees rotation of the system about a horizontal axis, as compared to FIG. 1. General rotations of the system relative to the configuration shown in FIG. 1 are also possible, eg, 90 degrees. The main impact of such rotations is on the wafer handling techniques.

In particular alternative embodiments of the invention, there may be no water in the measurement path. That is, the instrument is 'dry'. In such embodiments, the orientation of the instrument relative to the laboratory

may be arbitrary. For example, the embodiment of FIG. 1 could be operated on its side or upside down. While redesign some of optics might be preferred in such cases, it would not be necessary.

As one skilled in the art will recognize, the use of reflective optics in embodiments of the present invention may have advantages. There are at least three advantages of reflective optics. Fresnel reflections occur at the surfaces of refractive optics (ie lenses) and may be a source of systematic noise in the system. For example, light that has suffered a Fresnel reflection at an objective lens can arrive at the detector even if there is no wafer present. Thus, this light has no information about the wafer and is noise. In contrast, reflective optics generally do not suffer from Fresnel reflections. Refractive optics also can limit the bandwidth of the light that passes through them in two ways. Preferred embodiments with refractive optics use anti-reflective coatings (ARC) to minimize Fresnel reflections. Typically, ARC's are resonant structures that operate well over a limited spectrum of wavelengths. Outside of that range, their transmission is reduced, potentially limiting the bandwidth of the system. Also, the index of refraction of most materials is a complex function of wavelength. The imaginary part of the refractive index (K) describes attenuation of light at a particular wavelength as it propagates through the material. Thus, many lens materials can restrict the bandwidth of the system by having a large K at wavelengths within the desired spectrum. The second advantage of reflective optics is that they avoid attenuation of light as it propagates through lens materials. The third problem with refractive optics, which must be addressed is color correction. The real part of the refractive index, N, is also a function of wavelength. N affects, for example, the focal length of lenses. Therefore, lenses have chromatic aberration such that different colors focus at different depths. This is commonly 'corrected' by using materials with different spectral N for various components in the system. Since reflective optics do no use refraction to focus, they do not suffer from chromatic aberration do to the spectral changes in refractive index N.

Reflective optics, however, have certain constraints on aperture and geometry which make the refractive optics a preferred in certain embodiments. In these embodiments, optics are color-corrected for the semiconductor wafer immersed in water. The design of the optics considers the water as an optical component.

In the embodiment shown in FIG. 1, the optical measurements are made through window 120, which is fixed relative to the laboratory. Alternate embodiments than that shown in FIG. 1 utilize a novel window embodiment. FIG. 2A illustrates a prior art device with a single large window fixed relative to the laboratory. In FIG. 2A, wafer 200, water

surface 201, containment wall 203, objective lens assembly 207, beam splitter 235, relay optic 237, and window 202 are shown. It is noteworthy that this prior art device utilizes a single large window 202. For accurate measurements, window 202 must be of optical quality. Due to the size of the window, this can lead to considerable expense.

FIG. 2B shows a novel approach according to aspects of this invention. In FIG. 2B, wafer 200, column 201, small scanning window 202, detector optics 203, beam splitter 235, mirror 237, optical fiber 204, optical assembly 205, illumination optics 206, and objective lens assembly 207 are shown.

In FIG. 2B, a portion of the optical system is a column of water fixed relative to the objective lens assembly 207. The floor of column 201 is a small window 202. Column sides 209 rise to leave only a small gap between themselves and the wafer. Water flows into the column from supply line 206. A combination of surface tension and viscosity hold the water in place. Depending on the gap height, water may need to be flowing continuously to maintain a continuous column between the wafer 200 and small window 202. Additional jets may be used to remove bubbles. It is noteworthy in the above that the water column forms an optical element. Particular embodiments may comprise an extended water trough.

Referring to FIG. 2B, the watertight, scanning optical assembly 205 has illumination optics 206, which receive light from optical fiber 204. The illumination optics transmit a beam of light (which may or may not be collimated) through beam splitter 235 to objective lens assembly 207. Objective lens assembly 207 focuses the beam onto the wafer and collects the reflected light and sends it to mirror 237 as a (collimated or uncollimated) beam. The mirror deflects the light reflected from wafer 200 into the detector optics 203, which comprises a pinhole spectrometer and a vision system employing pattern recognition (not shown) to allow for precise positioning of the optical assembly 205 to pre-taught locations on the wafer. Mechanical translation stages (not shown) scan the entire assembly 205 with its water column and optics.

This aspect of the present invention has two advantages in comparison to utilization of a single large window and water bath. First, the objective always looks through the same portion of the window, so that its quality does little to affect the quality of the measurement. (Its effects can be removed by calibration). Second, because it is smaller than windows used in the prior art, it is much easier to obtain a very high-quality surface finish.

By properly designing the geometry of the water column as determined by the window 202, column sides 200, and supply line 206, water flow can be used to flush any bubbles that might be trapped within the column by the wafer. This is much easier for the relatively smaller area of interest in this invention than in the prior art, and does not require a specialized wafer handler to lower the wafer into a bath as does the prior art.

To achieve accurate results from the measurements, aspects of this invention use a reference reflector to correct for slowly varying characteristics of the measurement system. FIG. 3 shows an exemplary embodiment with a reference reflector. In FIG. 3, wafer 300, window 302, reference reflector 309, reference volume walls 310, reference volume 311, main volume of water 301, objective lens assembly 307 and relay optics 335 are shown.

In FIG. 3, reference volume walls 310 separate the reference volume 311 from the main volume of water 301. Reference volume 311 may be filled with air, water, or other suitable substances. An aspect of this invention is to ensure that the reflectivity of reference reflector 309 is very stable over time. The distance between window 302 and the reference reflector can be adjusted if volume 311 is not filled with water, to put the reflector in focus when the objective lens assembly 307 is the same distance below the window 302, as when the wafer is in focus. In a preferred embodiment, the volume is filled with an inert solid, and the height of the reflective surface above the window 302 is adjusted appropriately.

Reference reflector 309 may be of silicon, fused silica, chromium or any other inert material. It may comprise layers of deposited material on a substrate to achieve mechanical and optical stability. In a preferred embodiment, the reference reflector comprises a fused silica substrate with a chromium film on a top surface. An alternative embodiment of the reference reflector uses silicon with a reflective oxide layer on a lower surface.

Referring to FIG. 3, reference reflector 309, reference volume walls 310 and the window 302 may be assembled in a variety of ways. In a preferred embodiment, the reflector and window are hermetically sealed to the window. In an alternative embodiment, the reference reflector, reference volume walls and the window are held together with a polymer adhesive, eg, epoxy or super glue. In other embodiments, volume 309 is not sealed off from main volume 301. The components are either bonded together or held in place mechanically, for example with stops and springs. The reference volume is sealed in order to preserve the

reflectance of the reflector, ie., to avoid it getting dirty or corroded due to materials introduced into the bath, eg., CMP slurry. Sealing methods for volume 311 avoid the problem of breaks or leaks caused by different thermal expansion coefficients, either during operation or shipping.

In preferred embodiments, reference reflector 309 is placed in a position where the objective lens assembly 307 can have direct access to it. Preferably, the objective lens assembly can scan in at least one dimension, and move to the location of the reference reflector. However, in embodiments where the wafer scans over the objective, the reference reflector may do so as well. While a preferred embodiment has the wafer above the objective lens assembly as illustrated in FIG. 3, alternate embodiments may have the objective lens assembly above the wafer, or at an arbitrary inclination.

According to aspects of this invention described above, a reference spectrum from the reference reflector 309 is collected periodically. Following collection of a reference spectrum an algorithm utilizing the reference spectrum is used to calculate film thickness from spectra collected from wafer 300. Preferably, a reference spectrum is collected every time just prior to a wafer measurement. There are numerous ways to include the reference spectrum from the reference reflector into a data-reduction algorithm. In one embodiment, every spectrum from the wafer is normalized with the most recently measured reference spectrum from the reference reflector.

Calibration of the measurement apparatus may utilize a calibration wafer and the spectrum collected from it. Calibration adjusts the algorithm described above so that it gives the correct answer for the calibration wafer. The reference spectrum should be used by the algorithm at calibration in the same way that it is used during measurements of wafers, so that any changes in the system between the last calibration and the current measurement will not affect the results of the algorithm.

As described, embodiments of this invention (see FIG. 1 and FIG. 3) may include a reference reflector and dual spectrographs. The primary data for the measurement is the spectrum *S*, which is the system's output representing reflection from the sample under test. In addition to the properties of the sample, *S* depends on the characteristics of the broadband (UV, visible, NIR) illumination, the optical system, detectors and digitizers and other elements that comprise a measurement system. Such measurement system characteristics obscure information about the sample. Thus, an accurate measurement of film thickness should remove their effects.

In FIG. 1, a beam splitter divides the reflected beam from the monitor beam, which proceeds straight through the beam splitter to the spectrograph 141. The reflected beam proceeds from the beam splitter, through the objective and to the sample, back through the objective and beam splitter to a mirror which deflects it parallel to the monitor beam to spectrograph 140. It is understood that the paths from the beam splitter and mirror to the respective spectrometers may include other optical components which are not shown in FIG. 1 but are, in a preferred embodiment, as similar as possible for the two beams. In the case where the sample is the sample under test, eg, a wafer that has just been polished, the reflection spectrum is the measurement spectrum S, and its associated monitor spectrum is S_m. The monitor spectrum is used to correct for rapid changes in the system, eg, flickering of the illumination source.

This invention may utilize a reference spectrum S_r to correct for slowly varying characteristics of the system. S_r is the reflection spectrum from a sample in the system that has a very stable reflectance. There is a corresponding monitor spectrum S_{rm} collected at same time as S_r. The system can collect S_r, for example, every time a new wafer is being loaded into the instrument.

This invention may also utilize a calibration spectrum S_c to correct for constant or very slowly varying characteristics of the system. S_c is the reflection spectrum from a known sample. In addition to its monitor spectrum S_{cm}, there is an associated calibration reference spectrum S_{cr} and its monitor spectrum S_{crm}. The latter two spectra are collected just prior to or after S_c, which is collected when the system is put into service, and thereafter at long intervals, eg, 3 months.

Those skilled in the art will recognize that the spectra discussed above have a raw form, which is corrupted by various undesired components. Dark current and the readout current of the detector(s)corrupt the measured spectra. Parasitic reflections in the system may also act to corrupt the spectra, especially the reflection spectrum. If the objective reflects a portion of the illumination arriving from the beam splitter, the reflected light may corrupt the reflection spectrum. Therefore, all spectra are preferably corrected for these undesired contributions. Monitor spectra can be corrected by subtracting a 'dark' spectrum collected by the monitor spectrograph with the illumination source blocked. Reflection spectra can be corrected by subtracting a 'blank' spectrum collected by the reflection spectrometer with no reflector in place.

An aspect of this invention is to accurately measure the thickness of refractive index of films with quasi-normal incidence reflectometry. In preferred embodiments of this invention, a cost function constructed with the spectra measured by the instrument may be used to determine the thickness, without employing an intermediate calculation of surface reflectance.

As described above, the apparatus of this invention includes a calibration reflector, a reference reflector and a dual-beam spectrograph. The primary data for the measurement is the spectrum, *S*, which is the system's output representing reflection from the sample under test. In addition to the properties of the sample under test, the spectrum, *S*, depends on the characteristics of the lamp, optical system, detector and digitizer, which comprise the measurement system.

Since measurement system characteristics act to obscure information about the sample under test, an accurate measurement of film thickness should account for such effects. Some characteristics of a measurement system change significantly with time, and others may be substantially constant. In a preferred embodiment of this invention, an arc lamp is the light source. Flickering of the arc in it's housing produces very fast changes. Bending or flexing of source fiber 103 (see FIG. 1) and changing an optical path length due to scanning may give rise to fast changes. Aging of the lamp may produce slow changes. The numerical aperture, NA, is an exemplary characteristic of the system that remains essentially constant over time.

According to aspects of this invention, dual spectrographs may collect two spectra essentially simultaneously, a reflection spectrum from the sample under test and the monitor spectrum that does not interact with the sample under test, as shown in FIG. 1.

In FIG. 1 the sample under test is the semiconductor wafer 110. The sample may also be the reference reflector or the calibration reflector, as discussed above. From FIG. 1, the optical path for light determining the monitor spectrum may be similar to the optical path for the light determining the measurement spectrum, except for transit to and from measurement region 111. A preferred embodiment of the two beams is shown in FIG. 1. In preferred embodiments, the illumination source may be identical for both beams.

The method for data reduction used to determine film properties may be parametric minimization of a cost function. A preferred cost function contains the eight spectra identified above, as well as the parameters to be measured and other information known about the sample and measurement system. In a typical application, there might be a single parameter, eg, the thickness of a layer on the sample. In other applications, there may be two parameters, either the thickness of each of two layers, or the thickness of one layer and a parameter affecting the index of refraction of another layer. There also may be more than two parameters. The specific form of the cost function according to the preferred embodiments causes measurement system characteristics to balance, so that the minimization process depends only on the properties of the sample under test. Information about the measurement system preferably includes the noise characteristics of the spectra, for use in weighted optimization. Information about the sample might include the thicknesses and optical properties of various materials in the sample, as well as limits for some or all the parameters. As is known in the art, many types and strategies of minimization are possible.

A preferred cost function is

$$\chi^2 = \sum_{\lambda}\left[\frac{SS_{rm}S_{cr}S_{cm}R_c - S_m S_r S_c S_{crm} R_p}{W}\right]^2 \; 0,$$

where λ is wavelength, W is a weighting factor, R_p is a theoretically calculated reflectance based on the parameters p, R_r is another theoretically calculated reflectance based knowledge of the calibration reflector. All spectra, reflectivities and weights are in general functions of wavelength. The numerator has two terms $\sigma_1 = SS_{rm}S_{cr}S_{cm}R_c$ and $\sigma_1 = S_m S_r S_c S_{crm} R_p$. Each term is equally affected by the system characteristics. Therefore, the system characteristics do not affect the minimization. For example, S and S_m have the same rapid lamp fluctuations, as do S_{rm} and S_r, the numerical aperture (NA) of the system has the same effect on S and S_r, *etc.* Many other versions of the cost function are consistent with the teachings of this invention as long as measurement system effects cancel each other. Simplified versions, as compared to the above, are also consistent with this invention, eg, with the monitor spectra removed, or without the four spectra associated with the reference reflector. Minimization methods other than least-squares, as shown above, are possible as well, eg, mini-max or L1 methods.

It is noteworthy in the above that R_p and R_r are theoretically determined and not measured reflectances. Thus, the method of this

invention does not utilize measured absolute or relative reflectance spectra, as in some prior art methods.

Rapid wafer alignment with the optical system is another important aspect of this invention. FIG. 4 shows an exemplary embodiment of the wafer aligner according to this invention. In FIG. 4, wafer 403, rotary chuck 402, motor 412, water 404, window 405, water level 410, motor housing 400, rotary seal 401, light source 407, light 413, aligner window 408, detector 406, and tank wall 411 are shown.

In FIG. 4, rigid rotary chuck 402 holds wafer 403. Motor 412 turns the rigid rotary chuck about an axis (not shown). Water 404 fills the area above main window 405 up to water level 410 and over to tank wall 411. Rotary seal 401 seals motor housing 400 from the water. Light source 407 is also in a dry housing. The light source produces light 413 that passes through aligner window 408 from the dry housing into the water. Detector 406 is in the dry volume below window 405. Some of the light 413 strikes wafer 403 and is blocked. The rest of the light passes through main window 405 into the dry volume below it, and onto the detector.

Rigid rotary chuck 402 rotates wafer 403. As the wafer rotates, the edge of the wafer that is directly over the detector moves radially (to the left and right in FIG. 4). The radial motion arises due to the wafer being off-center on the rigid rotary chuck or not being perfectly round. Aside from machining tolerances, the presence of a fiducial notch or flat on the rigid rotary chuck causes the wafer to be out of round.

Radial motion of the edge of wafer 403 over detector 406 changes the shadowing of light 413 which falls upon the detector. The detector can be either a single long detector, eg, a photo-diode, or an array of detectors, eg, a CCD. In the former case, the total amount of the light falling on the detector is an indication of position of the edge of the wafer. As the edge of wafer 403 moves to the right in FIG. 4, the amount of light falling upon the detector decreases. In general, the output of the detector, I, is some function of the position of the edge of the wafer, x_e;

$$I=f(x_e), \tag{1}$$

that is not necessarily linear but is monotonic, so that its inverse

$$x_e=f^{-1}(I), \tag{2}$$

may be used to determine the location of the edge.

In an alternate embodiment, the detector may consist of an array of detectors, with each element in the array having a different location, x_a. In this case the intensity of light falling on the different detector elements gives rise to a waveform:

$$I(x_a)=g(x_e), \tag{3}$$

that can be processed by an algorithm, h, such that

$$x_e = h(I(x_a)) \tag{4}$$

Functions g and f will be complicated, due to wave-optics considerations (FIG. 4 is illustrative only of ray-optics). Determination of f or g is by calibration.

FIG. 5 illustrates calibration of the wafer aligner. In FIG. 5, spiral wafer 500, chuck 503, spiral edges 504 and 505, detector 506, and source 507 are shown.

Spiral wafer 500 has a thickness comparable to that of a silicon wafer; is made from a durable, clean, machinable, opaque material, eg, stainless steel; and has a mechanical index to insure that its center is aligned with the center of the chuck 503. As the chuck rotates, the spiral edges 504 and 505 block amounts of light emanating from source 507 from reaching detector 506. As the spiral rotates, the system records the detector output as a function of angle. The discontinuity in the radius of the spiral 505 indicates when the spiral is over the detector. The radius of the spiral as a function of angular displacement from the discontinuity 505 is known. Thus, the functions $g(x_e)$or $f(x_e)$ can be recorded, so that f^{-1} or h can be calculated for use with real wafers.

The outcome of the above-described measurement enables the calculation of the location of a notch or flat on the wafer, and the location of the center of the wafer with respect to the center of the chuck, from I for a set of rotations covering 360 degrees with f^{-1} or h.

FIG. 6 shows another aspect of the invention that improves the accuracy of wafer alignment. In FIG. 6, beam splitter 600, lens 601, reference detector 602, light source 607, window 608, rays 613, collimating lens 610, and wafer 606 are shown.

In general, the intensity of the source 607 can vary as a function of, eg, time and temperature. In order to correct or compensate for this, some portion of the light can be deflected by a beam splitter 600, possibly focused by lens 601, and detected by reference detector 602. The output

from the reference detector can be used either to control the output intensity of the source, or to correct the inversion of data for variations in the source.

FIG. 6 shows another exemplary illumination scheme. In this case the source 607 produces diverging light. In this embodiment, lens 613 collimates the rays 613. In other embodiments a collimated source may be used. Additional embodiments may uses a diffusing element following the source in order to homogenize the spatial mode profile of the source.

FIG. 7 illustrates the use of a large Field-Of-View (LFOV) camera and a small Field-Of-View (SFOV) camera to avoid groping in the process of locating a particular region of a wafer. In FIG. 7, die 700, LFOV 702, SFOV 703, LFOV pattern 704, and SFOV pattern 701 are shown.

LFOV 702 is generally larger than die 700, and much larger than the uncertainty in the location of the center of the wafer. Thus, it can be moved to location where it will certainly find LFOV pattern 704 on a die of a randomly oriented wafer. Once the LFOV pattern has been found, the system has much better knowledge of both the orientation of the wafer and the location of its center. Thus it is able to position the SFOV 703 over the SFOV pattern 701 without groping. This process has a deterministic time that is much shorter than the worst-case scenario for groping with just a SFOV, or than the time for physically aligning the wafer.

FIG. 8 illustrates the advantage of using of the LFOV camera to enable easy die size determination during training. In FIG. 8, dies 800, inter-die streets 840, inter-die alleys 850, die features 805a-c, large field of view 802, small field of view patterns 803, 804 and 801, and measurement site 806 are shown.

For training purposes, operators find it advantageous to view the wafer right side up, and moreover to orient the wafer so that inter-die streets 840 and alleys 850 appear vertical and horizontal, as shown in FIG. 8. However, such an orientation of the wafer is not necessary and other orientations are possible in alternative embodiments. An initial rough estimate of die size can be made from three occurances of a die feature, eg. 805a-c, selected by the operator on three different dies. The system can then use pattern recognition and the LFOV and/or SFOV cameras to obtain a very accurate determination of die size by locating LFOV and/or SFOV patterns, 804 and/or 801, on various dies on the wafer. With this method, it is not necessary for the operator to know the die size *a priori*.

Another advantage of the LFOV camera is ease of training operators to correlate measurement sites and patterns in the SFOV with the position on the wafer. Ideally, the large field of view covers a whole die, as shown in FIG. 8. Using large field-of-view 802, an operator can select the region of the die 800 to view with SFOV 103. This is similar to using a state map to navigate to a particular city. Once the SFOV has been properly positioned, the operator can very precisely select SFOV pattern 801 and the measurement site 806. This is similar to finding the correct intersection on a city map.

In a preferred embodiment, there may be a multiplicity of measurement sites within a die. In such cases, different sites may have different 'stacks' of layers that are to be measured. The thickness algorithm, ie, the parametric minimization of the cost function discussed above, generally needs to have *a priori* information, the algorithm recipe, about each stack that is measured. In cases where there are multiple sites per die with different stacks, the system must either use multiple algorithm recipes, or have a general algorithm recipe to accommodate the different stacks.

Another important aspect of this invention is an auto-focusing system for the objective optics. FIG. 9 shows a specular auto-focus system. In FIG. 9, sensor assembly 993, illumination source 991, detector 992, sensor 990, surfaces 902, 907, and 920, axis 996, illumination beam 900, and reflected beam 904 are shown.

The components in sensor assembly 993, illumination source 991, detector 992 and sensor 990 are rigidly held with respect to one another. Surface 902 is the nominal surface. The nominal surface has the correct distance z from the assembly 993 and is normal to the axis of the sensor 996. Surface 907 is an example of a surface displaced by ς from the nominal surface. ς is measured on the axis 996 of the sensor 990, as shown. Surface 920 is an exemplary surface tilted by angle ϕ from the nominal surface. The auto-focusing system components are the illumination source 991 and the detector 992. Illumination source 991 generates incident illumination beam 900 and detector 992 detects beam 904 reflected from the surface, eg, 902, 907 or 920. The angle between the beams and sensor axis 996 is θ when the surface is not tilted. The whole assembly 993 moves up and down with respect to the surface. The objective of an auto-focus system is to set the distance $\varsigma=0$ so that the distance between the sensor 990 and the surface, eg, 902, is some desired distance z, without regard to tilt ϕ. The system accomplishes this by adjusting the height of the assembly based on the output of the detector.

FIG. 10 illustrates an asymmetric specular auto-focus system. In FIG. 10, incident illumination beam 1011, nominal reflecting surface 1002, reflection point 1003, reflected beam 1004, detector plane 1005, nominal detection point 1006, deflected plane 1007, displaced reflection point 1008, displaced reflected ray 1009, and displaced detection point 1010 are shown.

An illumination source (laser, photodiode, white light, incoherent, coherent) generates incident illumination beam 1011 travelling toward a nominal reflecting surface 1002. The beam strikes the surface at reflection point 1003, where it produces reflected beam 1004. Particular embodiments may focus the illumination source on the nominal reflecting surface. In other embodiments, the illumination source may be unfocused. The reflected beam impinges on detector plane 1005 at the nominal detection point 1006. If the reflecting surface is displaced to another position, eg, 1007, there results a displaced reflection point 1008, a displaced reflected ray 1009, and a displaced detection point 1010. Thus, the downward displacement of the surface gives rise to detection displacement ξ_1. The detector lying on the detector plane 1005 indicates the displacement ξ_1 of detection point 1010 from the nominal detection point 1006. The detector could be a bi-cell detector, a position-sensitive detector (PSD), or a CCD array, or any other spatially sensitive optical detector. The auto-focus system then adjusts the height of the sensor assembly above the surface to cause ξ_1 to be zero.

FIG. 11 illustrates the sensitivity to tilt of an asymmetric specular auto-focus method. In FIG. 11, incident illumination beam 1100, nominal reflecting surface 1120, reflection point 1103, reflected beam 1104, detector plane 1105, nominal detection point 1106, deflected plane 1107, displaced reflected ray 1122, and displaced detection point 1123 are shown.

When the surface 1120 produces a tilted reflected beam 1122 whose location 1123 on the detector plane is displaced by ξ_2 from the nominal detection point 1106 due to the tilt. In this example, the distance from the aperture to the sample is in fact correct; however, the auto-focus would drive the aperture to a different height to compensate for displacement ξ_2. This new height would be erroneous, due to the effect of tilt on the optical system.

FIG. 12 shows a particular embodiment of the auto-focus system of this invention. In FIG. 12, assembly 1293, lamp 1291, spherical mirror 1250, detector plane 1205, lens 1295, beam-splitter 1294, nominal

reflected beam 1204, beam 1200, measurement surface 1202, and detector 1292 are shown.

The embodiment shown in FIG. 12 is sensitive to displacement of the surface, but not to the tilt of the surface. In this exemplary embodiment, detector 1292 is on the same side of the assembly 1293 as lamp 1291. Spherical mirror 1250 takes the original position of a detector plane in prior art devices. Lens 1295 optionally focuses the beam to minimize the spot size on the wafer or photo-detector. Beam-splitter 1294 allows the detector to be optically in the same position as the lamp. Mirror 1250 is selected so that its focal length is half the distance of nominal reflected beam 1204, so that it essentially images surface onto itself. It is noteworthy that the system of FIG. 11 has left-right asymmetry, in that light propagates only from left to right. In comparison, the system in FIG. 12 is symmetrical since light propagates both from left to right and from right to left in the figure.

FIG. 13 illustrates the increased sensitivity to surface displacement obtained by utilizing symmetrical specular auto-focus. In FIG. 13, incident beam 1300, entrance pupil 1301, illumination source 1391, detector 1392, focal plane 1314, nominal reflection point 1303, nominal reflected beam 1304, mirror 1320, focal plane 1314, nominal reflection point 1303, nominal reflected beam 1304, nominal detection point 1305, displaced surface 1307, displaced reflection point 1310, object point 1315, back reflected beam 1313, mirror reflection point 1312, image point 1316, displaced second reflection point 1317, re-reflected beam 1318, and detection point 1319 are shown.

In FIG. 13, illumination source 1391 and detector 1392 have been superposed for clarity so that in the figure the incident beam 1300 passes through the detector, which is not a practically possible. However, as one skilled in the art will recognize, the effect of this geometry can be realized either with a beam splitter as shown in FIG. 13, or by slightly displacing the entrance pupil 1301 and detector in opposite directions perpendicular to the drawing. The mirror has a focal plane 1314 that is imaged onto itself. The focal plane is centered on the nominal reflection point 1303, and normal to the nominal reflected beam 1304. For the nominal surface, the mirror 1320 reflects beam 1304 back along its path. This back-reflected beam is re-reflected from the wafer at nominal reflection point 1303 and returns to the detector along the same path as the incident beam 1300. The nominal detection point 1305 lies along the incident beam 1300. For the displaced surface 1307, the incident beam reflects from displaced reflection point 1310. The reflected beam passes through object point 1315 in focal plane 1314. The back reflected beam 1313 passes from the mirror reflection point 1312 through the image point 1316

to the displaced second reflection point 1317. The re-reflected beam 1318 then strikes the detector at the detection point 1319 that is some distance ξ_3 from the nominal detection point 1303. The detection distance ξ_3 is greater than four times ξ_1, the detection distance for a similar asymmetric auto-focus system. As ς increases, the angles between rays, eg, 1313 and 1304, become greater and the sensitivity increases further. Thus, the sensitivity of the symmetric system in FIG. 13 is greater than or equal to four times that of the equivalent asymmetric system.

FIG. 14 shows the insensitivity to tilt of the symmetric specular auto-focus system. In FIG. 14 nominal surface 1402, tilted surface 1420, incident ray 1400, nominal reflected ray 1404, reflected ray 1421, mirror 1422, and detector plane 1426 are shown.

In FIG. 14, surface 1420 is at the correct distance from the sensor assembly, but is tilted by angle ϕ. The reflected ray 1421 from mirror 1422 is tilted from the nominal reflected ray as a consequence, but is imaged back on itself by the mirror, so that the reflected ray hits the detector at exactly the nominal point 1403 in detector plane 1426. Thus, with the symmetric system, there is no erroneous offset generated by tilt.

A significant advantage of the SSA approach is that it can be configured in a straightforward manner to produce a linear error signal, with an auto-focus position at the zero crossing. Difference signals from any linear photo-detector (CCD, PSD, or bi-cell) can be used to supply the error signal feedback to correct focus. The operational dynamic range of the SSA is determined by; the f/# of the optics, the size of the photo-detector; and the angle of incidence to the surface.

FIG. 15 shows an alternate embodiment of the auto-focus system. In FIG. 15, lens 1500 and plane mirror 1501 are shown. The embodiment illustrated in FIG. 15 comprises lens 1500 and plane mirror 1501, which can replace the spherical mirror in other embodiments (see FIG. 14 for example). The focal length of the mirror is equal to the distance for the nominal reflection point to the lens' center. The distance from the lens to the mirror is also one focal length of the lens. This reduces the sensitivity by roughly a factor of two in comparison to a system with a spherical mirror. FIG. 16 illustrates the insensitivity to surface tilt of the embodiment shown in FIG. 15. In FIG. 16, lens 1600 and plane mirror 1601 are shown.

In the above description and figures, beams have been discussed and represented as lines. In some embodiments, the beams can be focused, eg., on the wafer with a lens. Both symmetric systems roughly

refocus the beam on the surface at re-reflection, if it is focused at reflection.

Another aspect of the present invention is wafer handling. In many applications, a wafer handler receives the wafer from a robot, with the device side of the wafer facing down. In a preferred embodiment f this invention, a wafer handler receives the wafer on a wafer ring with wafer supports, as shown in FIG 17.

The wafer ring in a preferred embodiment has at least three positions relative to the chuck. In a first position, illustrated in FIG. 18., the wafer ring is far enough from the chuck that the robot can place the wafer onto the wafer ring, as shown. In the second position, as shown in FIG. 19, the wafer ring draws the wafer up against the chuck, so that a vacuum applied to the chuck holds the wafer. In the third position, as shown in FIG. 20, the wafer ring drops slightly away from the chuck such that:

1) it does not touch the wafer; and

2) it is close enough to the chuck so that it will catch the wafer in the event of loss of vacuum clamping.

This position allows the wafer on the chuck to rotate, while keeping it safe.

The wafer handler in FIG. 17-FIG. 20 has three distinct advantages as compared to prior art devices. In the prior art, a suction cup on a wand typically picks up the wafer and lowers it into the measurement position, where it either rests on points around its edge, or is slighty bowed by downward force of the wand. In contrast with the present invention, prior art devices do not:

1) allow the wafer to be oriented;

2) may drop the wafer a significant distance if the vacuum is lost; and

3) may not hold the wafer flat on a chuck.

There are a number of constraints on the manner in which the wafer is handled. The wafer is presented to the instrument with the device side down. It is necessary to contact the wafer only in the exclusion zone around its perimeter, eg, the outer 3 mm annulus of the wafer. There can be a significant uncertainty in the hand-off position where the robot is attempting to set wafer. Also, it is undesirable to obscure the view of the wafer from below, so that the instrument can see as much of the wafer's surface as possible.

According to preferred embodiments of this invention, Two methods to meet the above-described constraints are illustrated in FIG. 21 and FIG. 22. In FIG. 21, a wafer support is attached to the wafer ring to hold the wafer. The top surface of the wafer support is sloped so that

regardless of the location of the wafer, the wafer support touches only the very edge of the wafer. In the embodiment shown, there are at least three supports distributed around the circumference of the wafer. Each wafer support is sufficiently narrow (in the dimension perpendicular to figure), to cause as little obscuration as possible. In FIG. 21, the wafer is shown with its center coaxial with that of the wafer ring. Do to the uncertainty in the hand-off position, the wafer could be either to the left or the right. The required length of the wafer support is determined by the hand-off uncertainty. An another embodiment of the invention, shown in FIG. 22, the wafer support has two slopes. The outer slope causes the wafer to be centered, regardless of the hand-off position of the wafer.

In an alternative embodiment, the wafer is gripped by its edge, rather than held by either supports or a vacuum chuck. The grips may optionally rotate the whole wafer for alignment in one or more axes.

In a preferred embodiment, the chucked wafer is lowered into a water bath where the optical measurements are made. If the wafer is lowered straight down into the water, it is likely to capture bubbles under its surface that would have a deleterious effect on pattern recognition and spectroscopic measurements of thickness. In order to reduce the tendency to trap bubbles, it is advantageous to lower the wafer into the water so that their surfaces are not parallel during the operation. In the prior art this has been accomplished with the wand referred to above and a cam.

In the current invention this is accomplished with a linkage, as shown in FIG. 23-FIG. 25. There are two support pivots, one on either side of the chuck assembly, which support the weight of the chuck assembly, and are driven up and down. The chuck is at the bottom of the chuck assembly. The motion of the chuck housing is further constrained by the combination of the stationary tilt anchor, the linkage and the tilt arm. These three components are roughly on a plane perpendicular to and bisecting the line the attaches the two support pivots. The linkage is attached to both the tilt anchor and the tilt arm by pivots.

In the particular embodiment shown in FIG. 23, the support pivots are in their highest position. As the support pivots lower, as shown in FIG. 24, the lowering chuck housing pulls down the left end of the linkage. The linkage swings to a more horizontal position. As it does so, it pushes the tilt arm to the right, which, in turn, forces the chuck housing to rotate clockwise. In this manner, the wafer (not shown, but on the bottom of the chuck assembly) is held at a non-horizontal angle when it breaks the surface of the water. As it chuck assembly further lowers, it displaces water, so the water level water rises.

In this exemplary embodiment, as the support pivots continue to lower, the linkage rotates beyond horizontal, and as it does so, it pulls the tilt arm to the left, causing the chuck housing to rotate counter clockwise. Eventually, at the bottom of the travel of the support pivots, the chuck housing is held roughly horizontal by the combined efforts of the support pivots and the linkage. The precise position and rotation of the chuck housing at the bottom of the support pivots' travel is determined by kinematic hard stops. These are adjusted so the wafer is parallel to the x and y motions of the optical system which is below the support plate. The support plate has the main window in it, which allows the optical system to 'see' the wafer.

In preferred embodiments, there are two sensors to control the water level. The low-level sensor is used to insure that there is enough water for the system to operate as designed. The high-level sensor is used to prevent the system from overflowing if the drain becomes blocked.

In other embodiments the wafer could descend into the water with its surface horizontal, ie, parallel to the mean water surface. In this case bubbles will be trapped with high probability. There are several means for removal of such bubbles after they have formed including, water jets from the periphery of the wafer (and window), a squeegee, a water knife (like a windshield wiper, with high-velocity water substituting for the squeegee), and an ultrasonic beam. It would be possible to recognize the presence of bubbles from analysis of either the image or the measurement spectrum, and to control the bubble removal on that basis.

The wafers that come to the instrument after CMP have not been cleaned, and will have slurry on them. Over time, this slurry may cause the main window between the wafer the optics to become dirty. Air-borne particulates could also cause the main window to become dirty. Several techniques can be used to clean the main window, either alone or in concert. A preferred method comprises:

1) draining the water;

2) wetting the main window fully with a cleaning solution (eg, isopropal alcohol);

3) laying an absorbent fabric onto the main window so that its whole surface is covered; and

4) drawing the fabric off the wafer from the center so the perimeter of the fabric is drawn across the wafer.

Given the low clearance between the main window and the chuck in its highest position, this operation may be difficult to perform. An arm

designed to deploy the fabric and draw it off from the center may be advantageous. An addition method employs an ultrasonic cleaner to help dislodge particles from the surface of the main window. Once the particles are dislodged, continuous flow of the water down a drain may be sufficient to keep the main window clean. Scrubbing may be necessary to dislodge particles. A squeegee (eg, like a automobile's windshield wiper) may be more effective at displacing the particles than drawing off the fabric, as described above.

Given the tight constraints on the size (footprint) of the instrument in a CMP (or other) tool, and the size of the moving parts of the optical system, it can be difficult to scan the whole wafer. Further, there may be obstructions between the wafer and the optical system, such as the wafer supports attached to wafer ring, described above. In these cases, another advantage of aspects of this invention is to allow the optics to 'see' absolutely any point on the wafer, as shown in an exemplary embodiment in FIG. 26.

In the particular embodiment of FIG. 26, the view is looking up at the wafer. The wafer is above the supports that are held by the wafer ring. As described above, the vacuum chuck supports the wafer, and the supports are not touching the wafer at this time. The scan range of the optics does not cover the full area of the wafer. The target, in its initial position, is obscured both because it falls outside of the scan range and because it is above the wafer support. Rotating the wafer so that the target is in the rotated target position allows the optics to 'see' the target. This is important especially when scans of thickness along a diameter of the wafer are desired to measure radial uniformity of the CMP process.

Another aspect of this invention is to use a vacuum chuck to flatten the wafer. Prior art devices hold the wafer by its periphery on a ring, either by gravity or by a wand depressing the center of the wafer slightly. In the former case, the natural warpage of the wafer, eg, due to stresses from films, causes the wafer surface to be non-planar. In the latter case, the warpage of the wafer is overcome by a different, more repeatable non-planarity. Using the vacuum chuck to flatten the wafer according to this invention eases auto-focusing, and reduces effects due to varying optical path length (including through the water) and tilt.

Wafer planarity is desirable for two reasons. To avoid tilts of the wafer surface relative to the optical beam for making, eg, thickness measurements. The reflection coefficients from the wafer are functions of angle, so that tilts can produce an error in any measurements based on reflectivity. The second reason has to do with focus. If the optical path through the water changes due to non-planarity of the wafer, it will

degrade the focusing ability of the optical system due to aberrations. The third reason has to do with auto-focus. With any auto-focus system that does not have the same effective angle of incidence as the measurement beam, there will be a residual error between where the auto-focus system is in focus and the where the measurement beam is in focus. This is because the objective is focused by changing an optical distance in air to compensate for an change in optical distance in water, and refraction of the light beams.

A through-the-lens auto-focus system is an alternative to the auto-focus system described above. The apparatus can transmit and receive the auto-focus light through a beam splitter that replaces one of the turn mirrors in the system. A beam would be launch along the collimated measurement or monitor beam and ultimately up to the wafer where it is reflected and travels back along a collimated beam (the same or another), where it is detected after passing through a beam splitter the same or another). One method that could be used in this manner is that used in CD's. An astigmatic focused beam shines on a quad cell, whose four cells are designated N, S, E, W, as the points of a compass. If the beam is defocused in one direction, it spreads in the N and S directions, and contracts in the E and W directions. If the beam is defocused in the other direction, it contracts in the N and S directions, and spreads in the E and W directions. The spreading and contracting on the quad cell can be detected electronically and used to control the focus of the measurement system.

Further, there are three distinct advantages to having a wafer aligner:

1) during training the operator can always view the wafer right-side-up, eg, with the notch in the direction towards the bottom of the view screen. This makes training of the system easier;

2) pattern recognition is more difficult with arbitrary orientations of the wafer. The better the initial alignment, the easier is pattern recognition; and

3) with an aligned wafer, the pinhole can have a square cross section (perpendicular to the measurement or monitor beams), which allows for greater light transmittance without an increase in t he minimum box size that can be used for the measurement, if the 'box' that the measurement is made in is also square, as is typically the case.

Another aspect of this invention is a software joystick. The problem is how to allow the user of a software system for a motor controlled camera to move the camera to locate features. In preferred embodiments of this invention, the user will not have physical access to the motors moving the camera. The camera view displayed in the software may be

less than 0.01% of the area covered by the full motion of the camera. The user needs to be able to move the position of the camera to see other parts of the total available view.

This type of issue may be resolved through the use of a physical device consisting of a control stick connected to one or more position detecting transducers. The user moves the stick's position. The position is translated into relative speeds of the motors moving the camera. The view of the camera is continuously updated to allow the user to see where the camera is positioned. This type of device is called a joystick. It is a handy device because it is easy for a user to associate the position of the stick with the motion of the camera. This is particularly true of a multi-dimension joystick.

The following paragraph refers to a standard software control called a slider bar or slider. This software control on a graphical user interface is displayed to look like a sliding potentiometer. The user can change a value associated with the software control by using the mouse pointer to move the position of the slider on the screen. This type of control often has a pair of arrows. If the user selects one of the arrows, the value of the slider changes in the direction that the arrow points by some fixed amount.

As in particular embodiments of according to this invention, it may be desirable to not have joystick hardware. In other software systems, the separate hardware transducers of the joystick are often replaced with software controls. For example, a two dimensional joystick could be replaced with two slider bars. It is also possible to replace a two dimensional joystick with four arrow buttons, pointing at 90 Degree angles from each other. In such a system each time the user selects one of the four arrow buttons, the camera moves by a fixed amount in a direction dictated by the arrow. With this type of system the user might control the amount the stage moves with each selection by using a slider or numeric text field. The four arrow buttons could be replaced or added to through the use of the four keyboard arrow keys, often used to move a text cursor. These types of software solutions make it difficult for the user to move the camera along a line not lying on one of the axis of the motors. They can also be difficult to associate and change the speed of the motion.

According to aspects of this invention, software is utilized while maintaining the non-axis moves and easy speed control of the hardware joystick. The software control device according to this invention may hereinafter be referred to as a software joystick. The software joystick is designed to control two dimensions of motion in a coordinated fashion. It may be represented on a screen as a circle. Selecting and holding a

mouse button within the control area of the software joystick is like holding onto the handle of a hardware joystick. The position of the mouse cursor within the control area may be used to determine how to control the motion of the camera. Releasing the mouse button within the control area of the software joystick is like releasing the handle of a hardware joystick.

In a particular embodiment, the control area of the software joystick is a rectangle around the circle. If the cursor is inside the circle when the mouse button is released, control values of the software joystick return to the values at the center. If the mouse button is released within the rectangular control area but outside of the circle, the control values of the software joystick remains at the last selected values.

To understand the operation, it is good to imagine a horizontal and vertical line through the center of the circle. These two lines divide the circle into four quadrants with standard Cartesian coordinates. The software joystick may have two control values, one for the horizontal (X-axis) and one for the vertical (Y-axis). Each value may be a monotonic function of the distance from the center of the circle.

This graphical user interface software control may allow the users of our software to control the motorized position of the camera with coordinated multi-axis motion. It may also allow easy modification of the speed of either or both axis.

Embodiments of the present invention comprise both systems for determining film thickness and a profilometer to determine amounts of recess, dishing, or other departures from planarity of a wafer surface. Details of aspects of such embodiments are in Appendix A.

In preferred embodiments, the profilometer may be coupled to the same optics breadboards shown in FIG. 1 for reflectometer system 100. Preferred embodiments may also require the use of flexural bearings for smooth repeatable motion on micrometer or sub-micrometer scales. These embodiments find great applicability for use on wafers with both dielectric and metal structures.

In different embodiments, the profilometer may be an acoustic profilometer or an optical profilometer. A particular embodiment of an optical profilometer may use the auto-focus system described above to determine a relative profile of a wafer surface. The auto-focus system is inherently sensitive to the profile of the wafer surface since departures from planarity of the wafer surface will cause differences in the focussing of light rays reflected from the wafer surface.

Other embodiments of this invention may include apparatae for high-contrast imaging of the wafer surface. Particular embodiments may utilize aspects of differential interference contrast (DIC) techniques. Polarization techniques may be incorporated to infer quantitative information about the wafer surface according to techniques well known in the art. In particular embodiments, an integrated interferometer, and imaging spectrograph may be used to simultaneously determine the wafer surface's profile and material content. Other embodiments may comprise an ellipsometer. Preferred embodiments comprise motion control systems, image pattern recognition systems, and software to determine the quantities of interest from measured data.

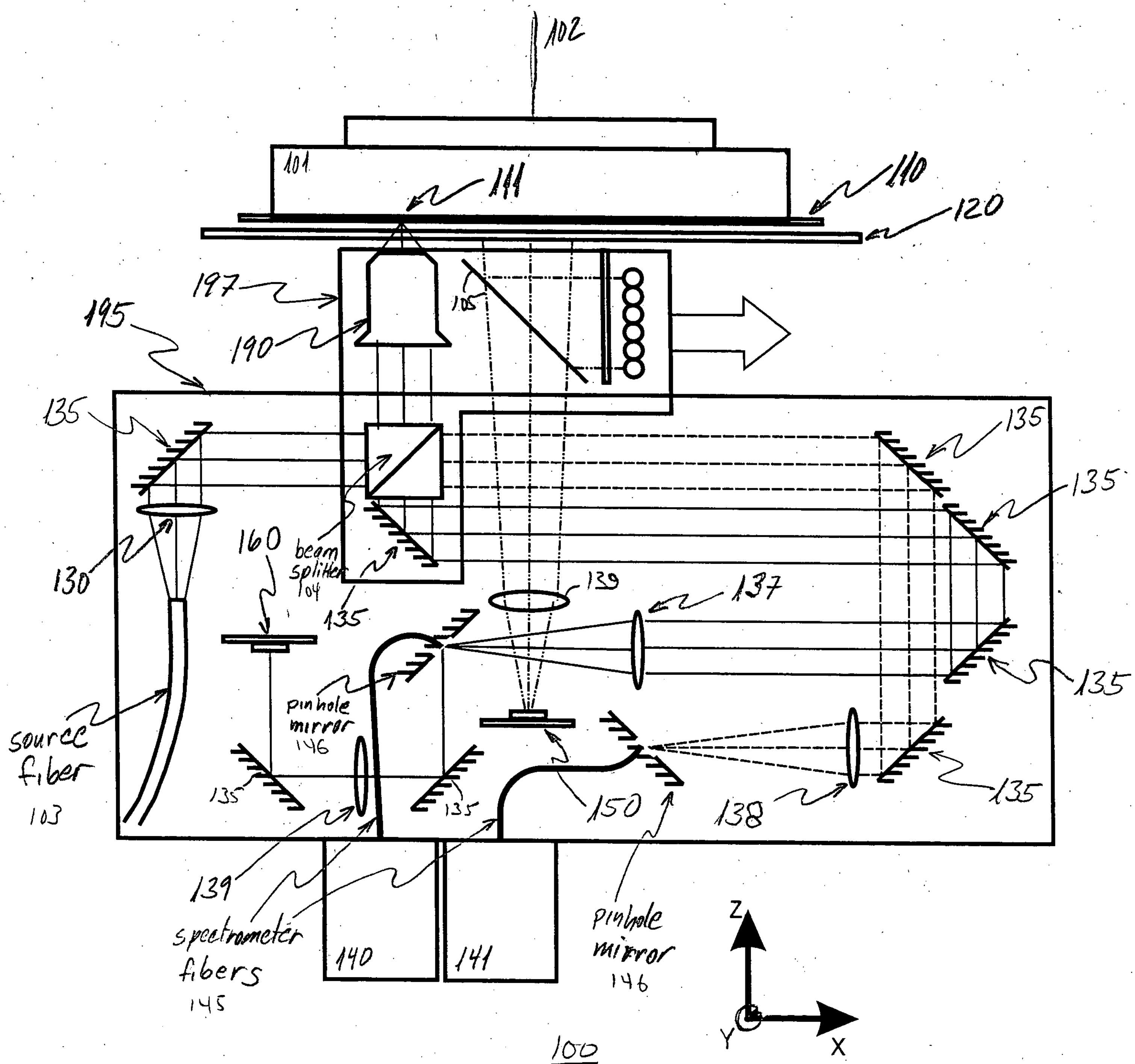
As described, the optical system according to the present invention may also be used to infer erosion of the wafer surface. It is also suitable for use in wafers with closely spaced metal and dielectric structures. In cases where the presence of metals or other materials must be accounted for in the data analysis, different embodiments of this invention may utilize empirical calibrations or theoretical models or a combination of theoretical and empirical methods.

It is noteworthy that aspects of this invention, as described, allow measurements to be taken over the wafer surface at differing rates. The time scales for data collection, processing and the movement from measurement region to measurement region, etc. are adjustable and depend on the results desired.

An aspect of this invention is precision positioning of optical systems relative to patterns on a wafer surface. Optics breadboards (see FIG. 1) may be positioned with a direct drive motor/lead screw. In a preferred embodiment, components of a motor are mounted directly on a lead screw shaft (see Appendix A). According to this invention, by eliminating coupling elements, a more compact, torsionally stiff and alignable drive mechanism results.

Embodiments of this invention may be integrated into a wafer fabrication line. As described above, different embodiments of this invention allow it to be at different positions relative to the wafer under test. Particular embodiments utilize raiser and feeder elements (see Appendix A for detail) to take wafers from other locations and introduce them to an apparatus according to this invention.

The foregoing description of various embodiments of the invention has been presented for purposes of illustration and description. It is not intended to limit the invention to the precise forms disclosed. Many modifications and equivalent arrangements will be apparent.



102
101
111
110
120
197
105
195
190
135
130
160
beam splitter 104
139
137
pinhole mirror 146
source fiber 103
150
138
spectrometer fibers 145
140
141
pinhole mirror 146
Z
Y
X
100

Fig 1

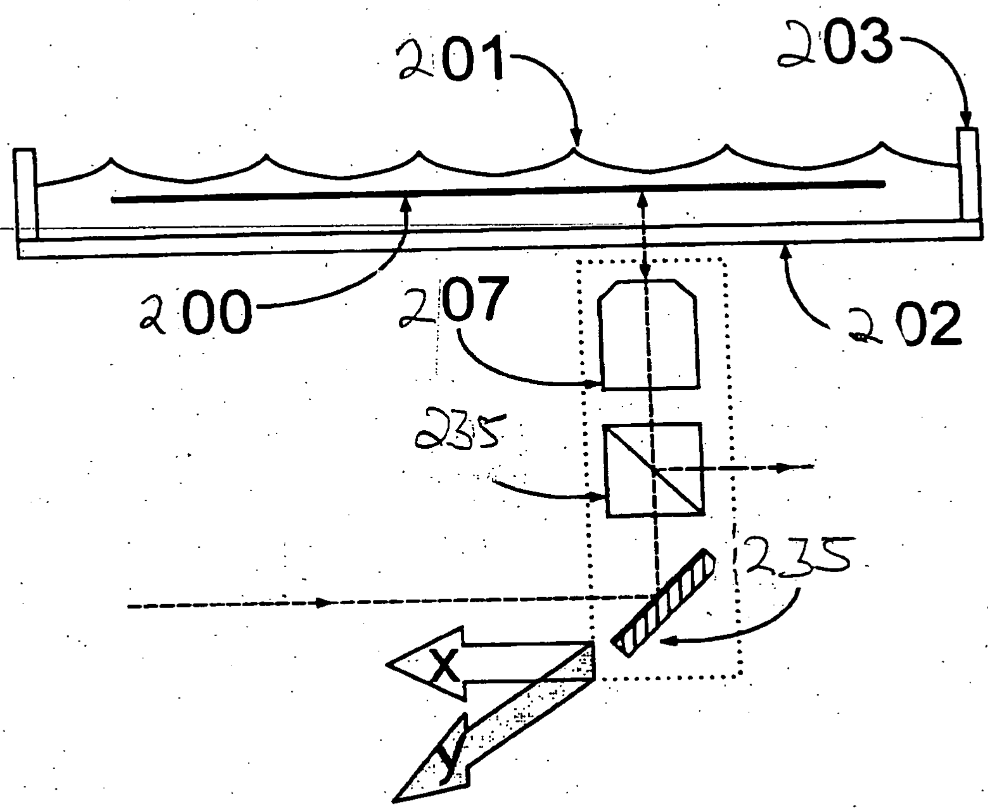


Figure 2A (Prior art)

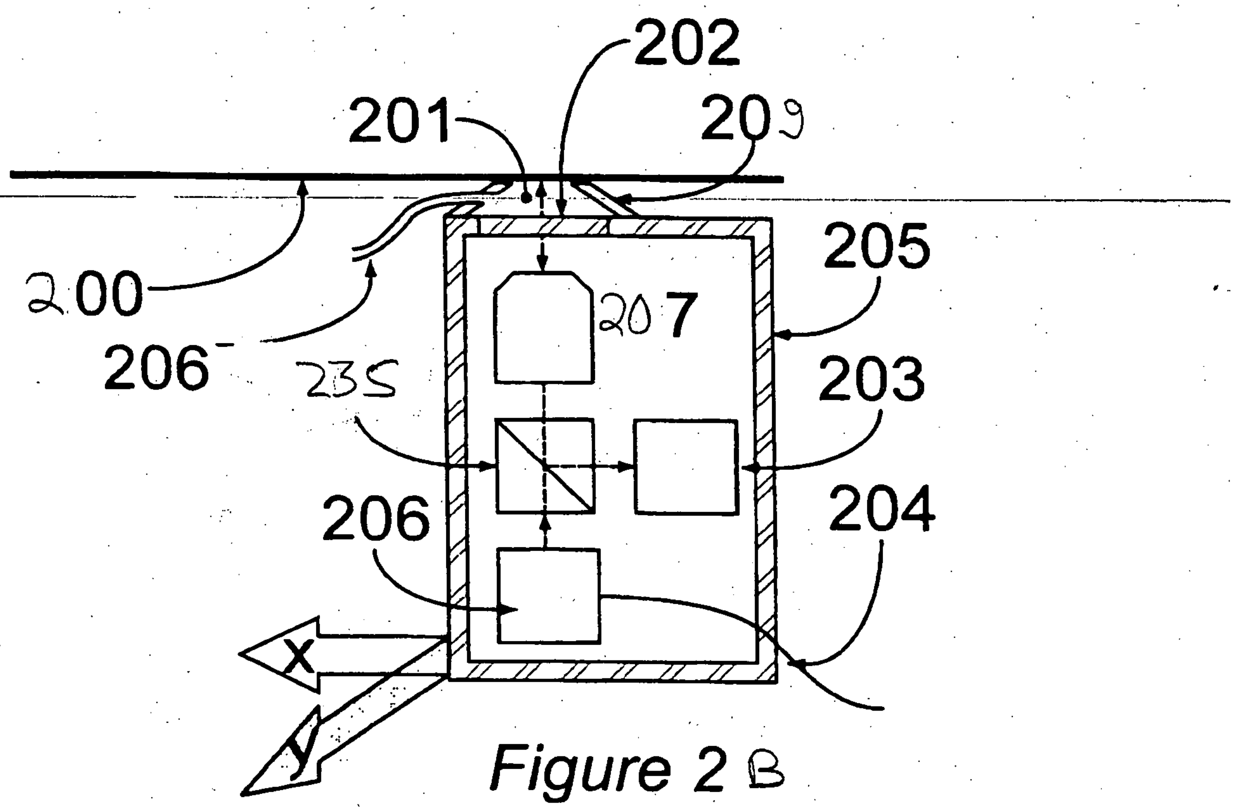


Figure 2 B

Received Time Jan.18. 11:28AM

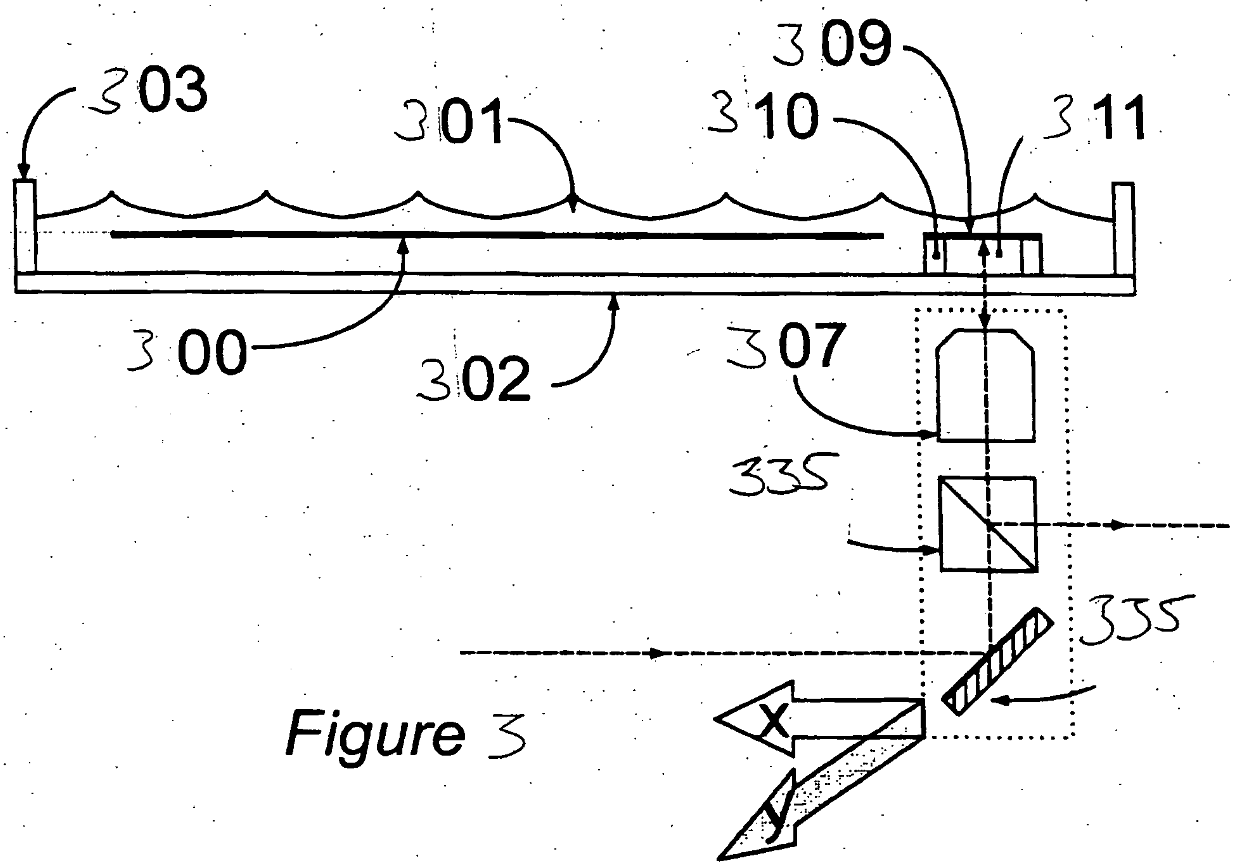


Figure 3

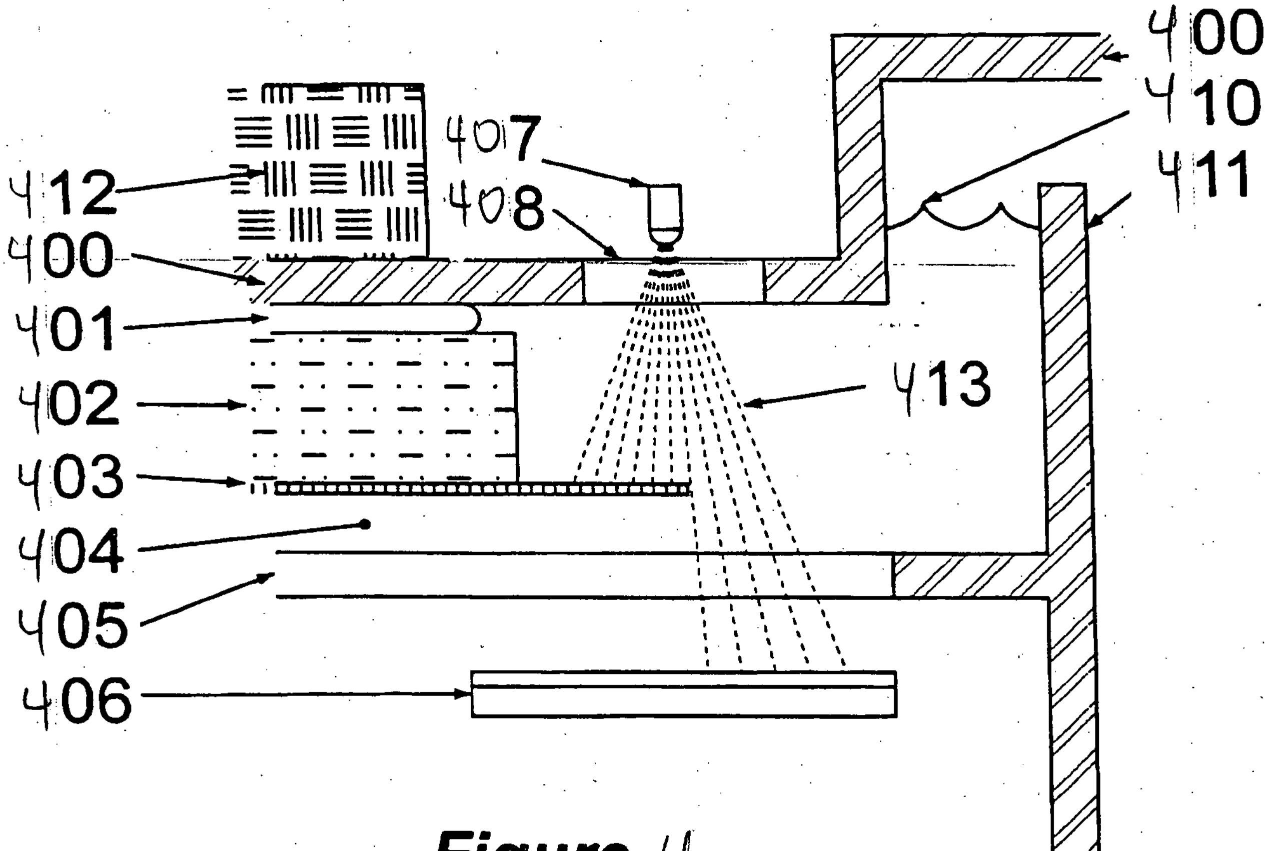


Figure 4

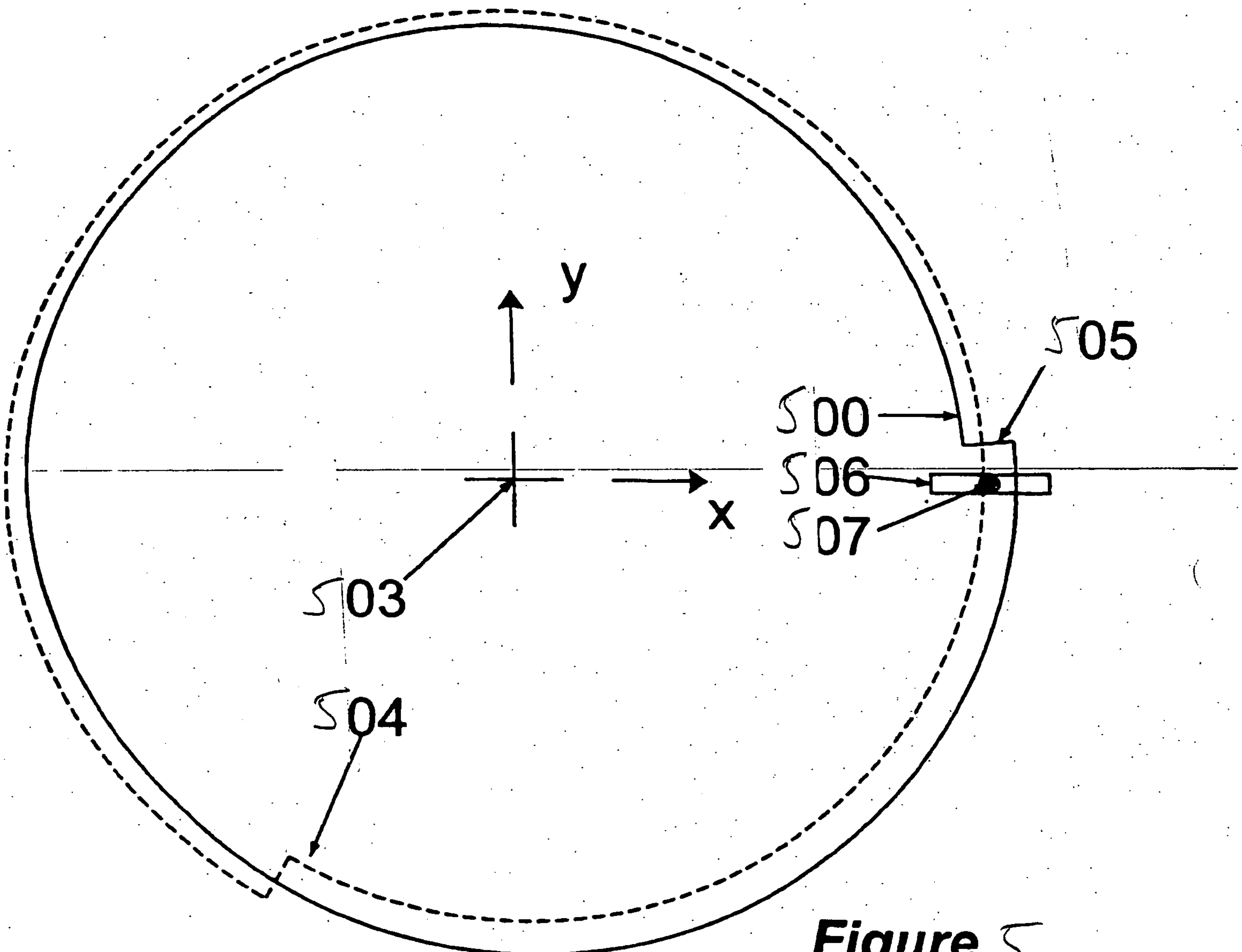


Figure 5

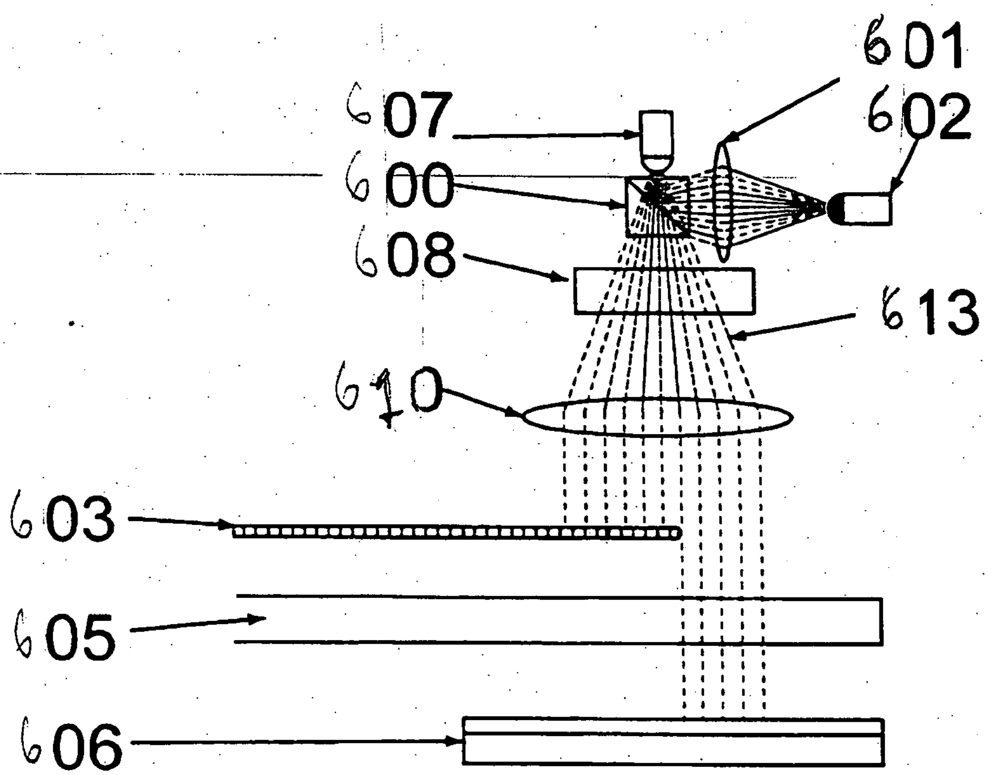


Figure 6

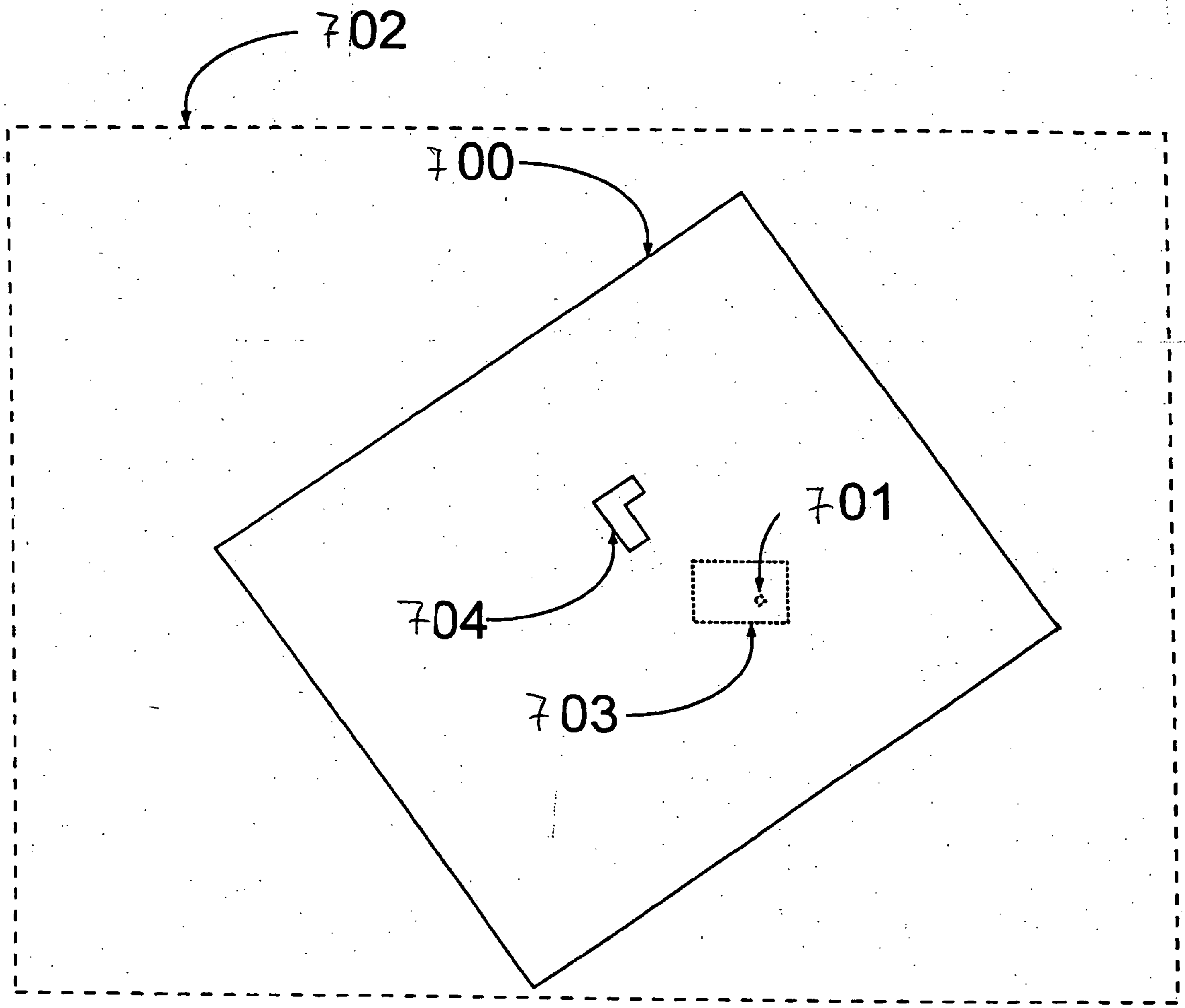


Figure 7

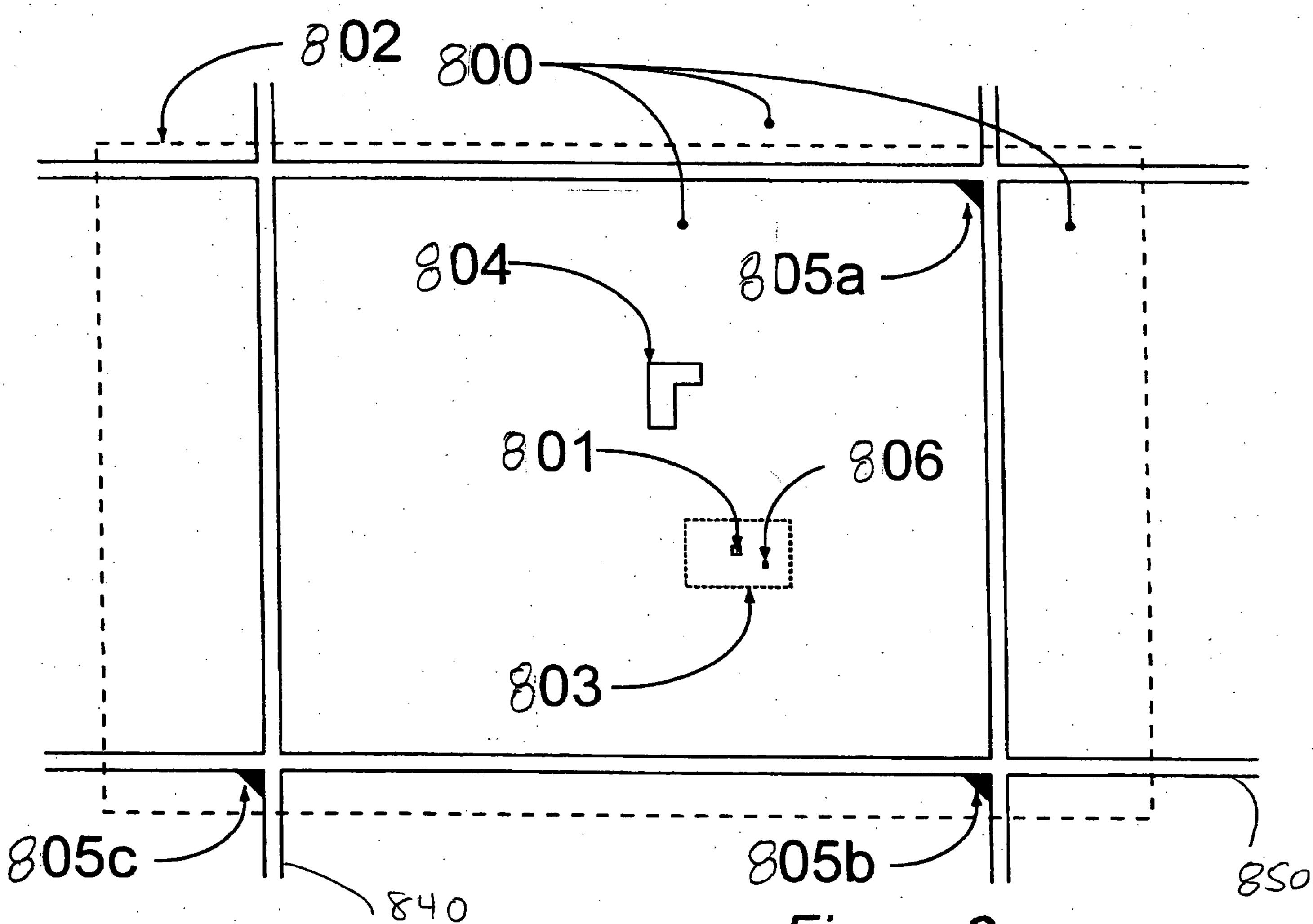


Figure 8

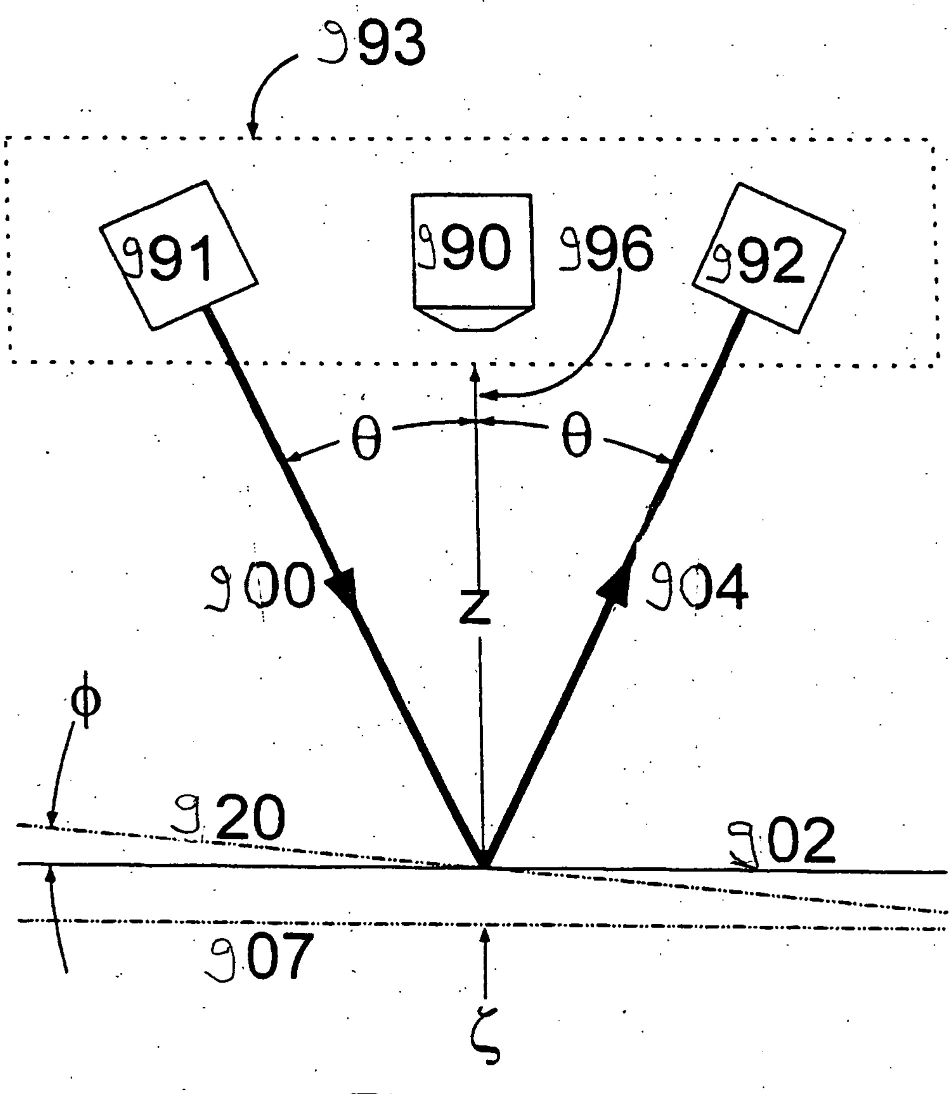


Figure 9

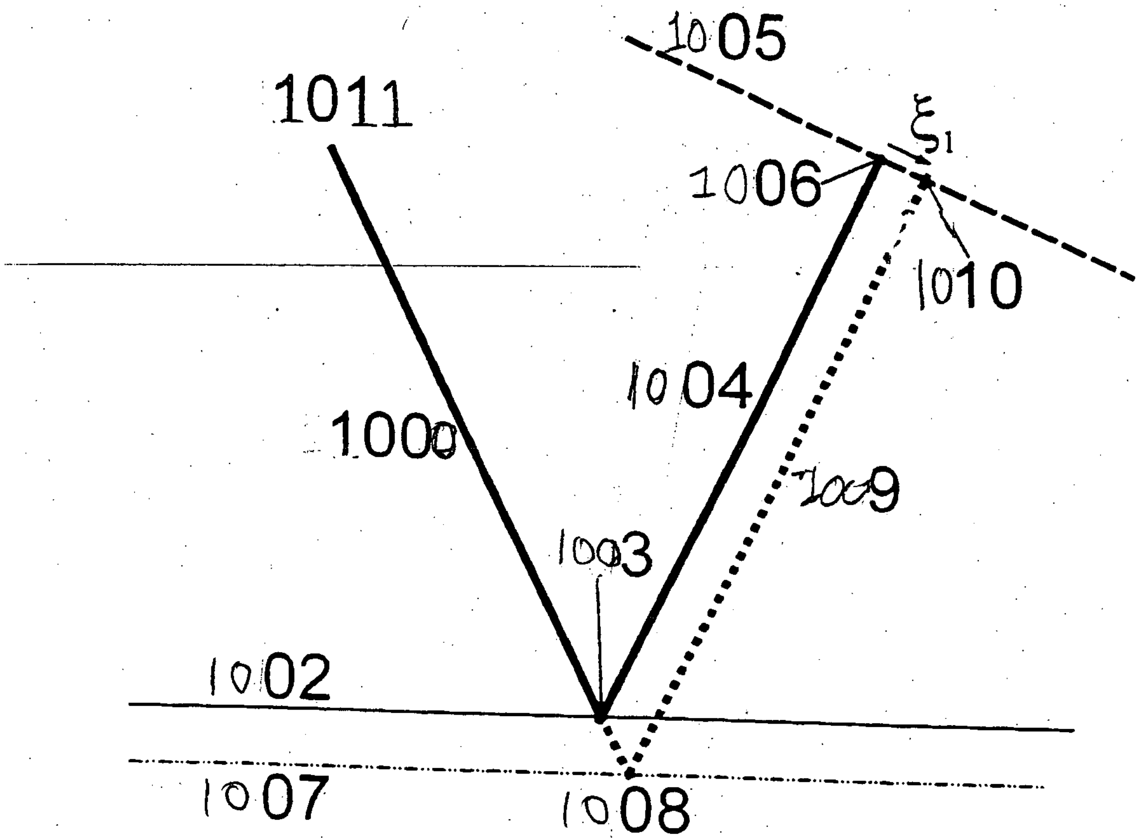


Figure 10

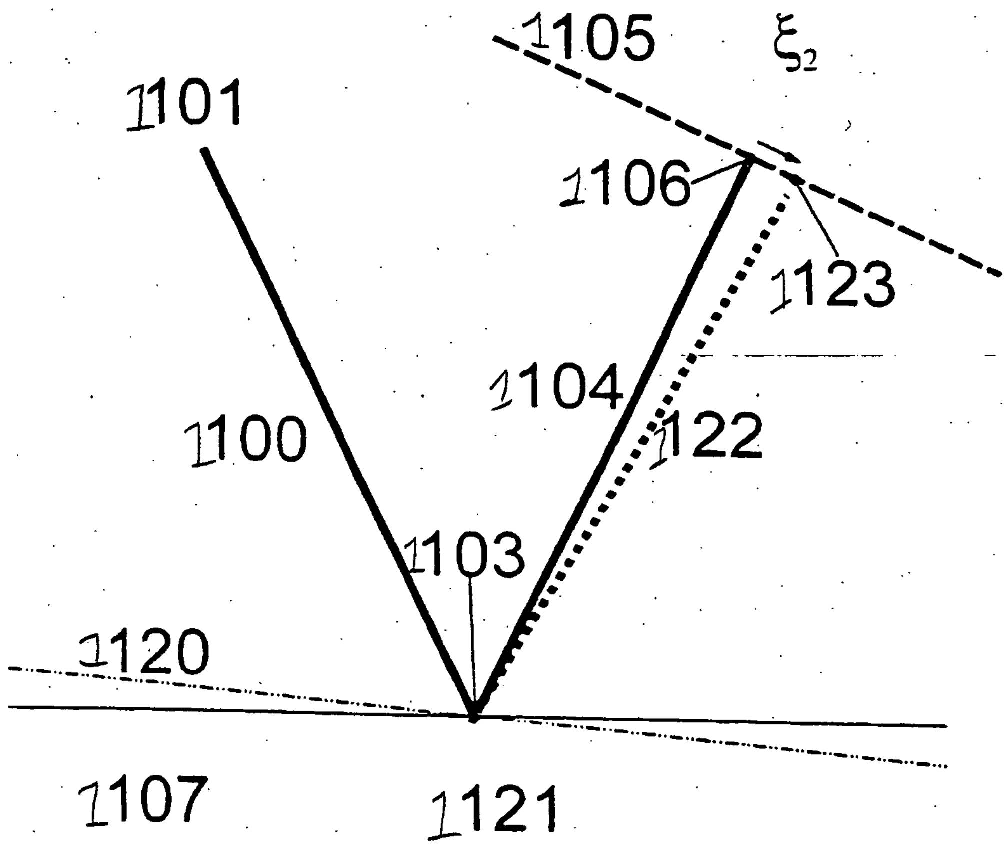


Figure 11

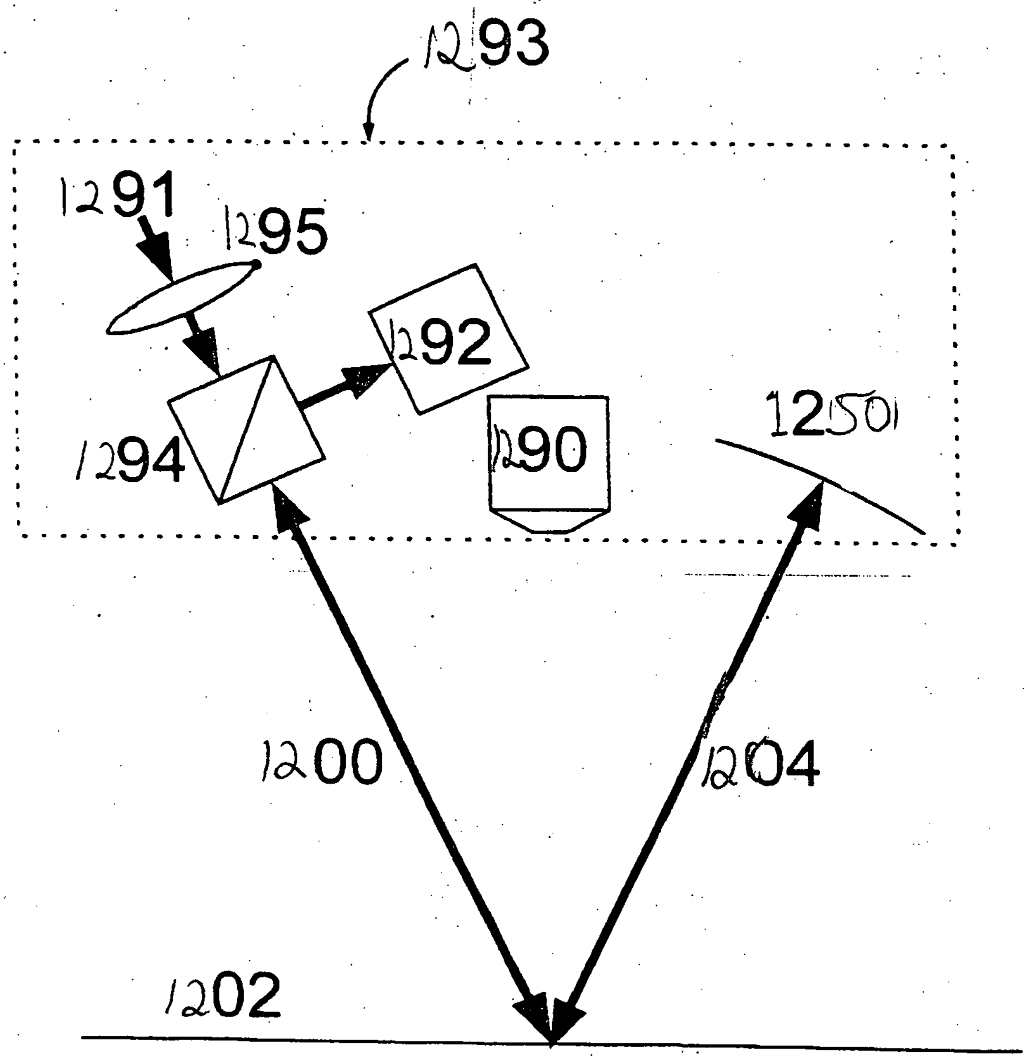
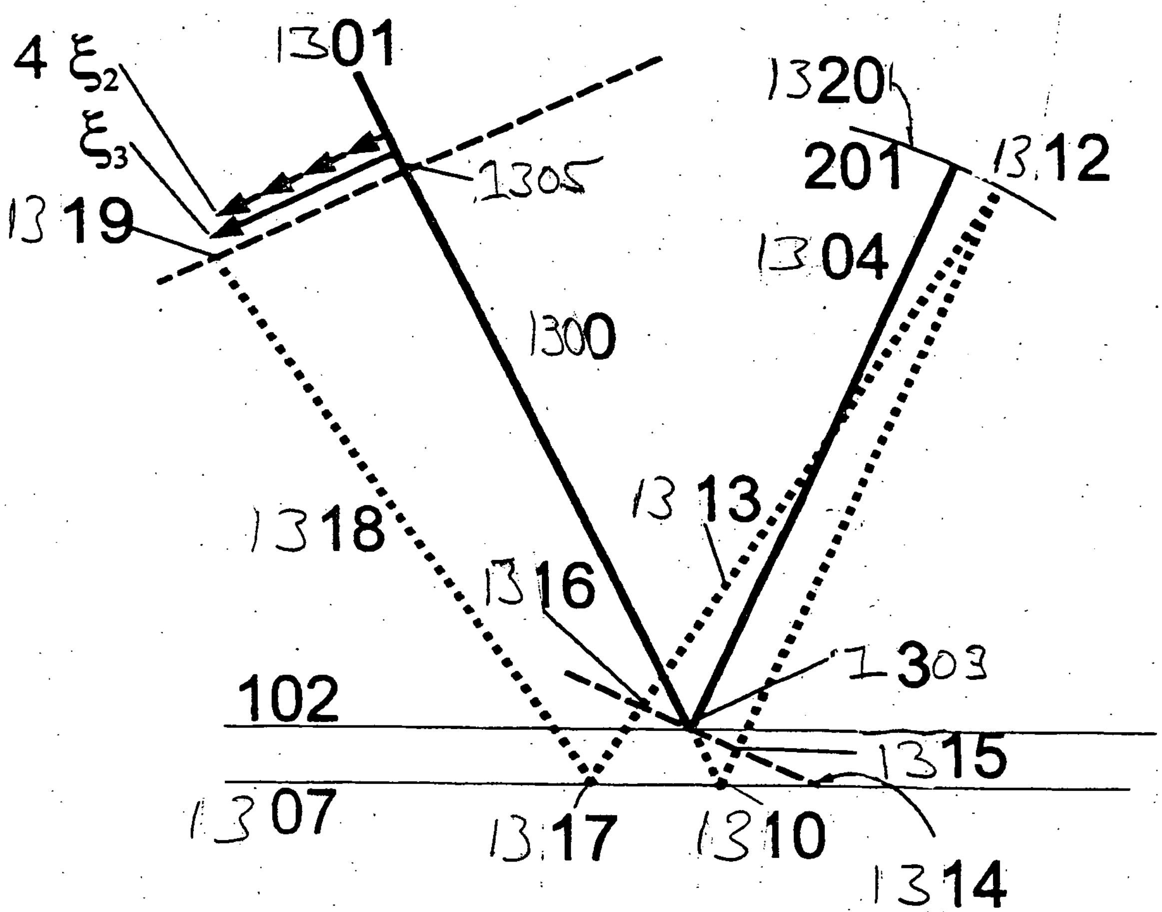


Figure 12



4 ξ_2
ξ_3
1301
1305
1320
201
1312
1319
1304
1300
1318
1313
1316
1303
102
1315
1307
1317
1310
1314

Figure 13

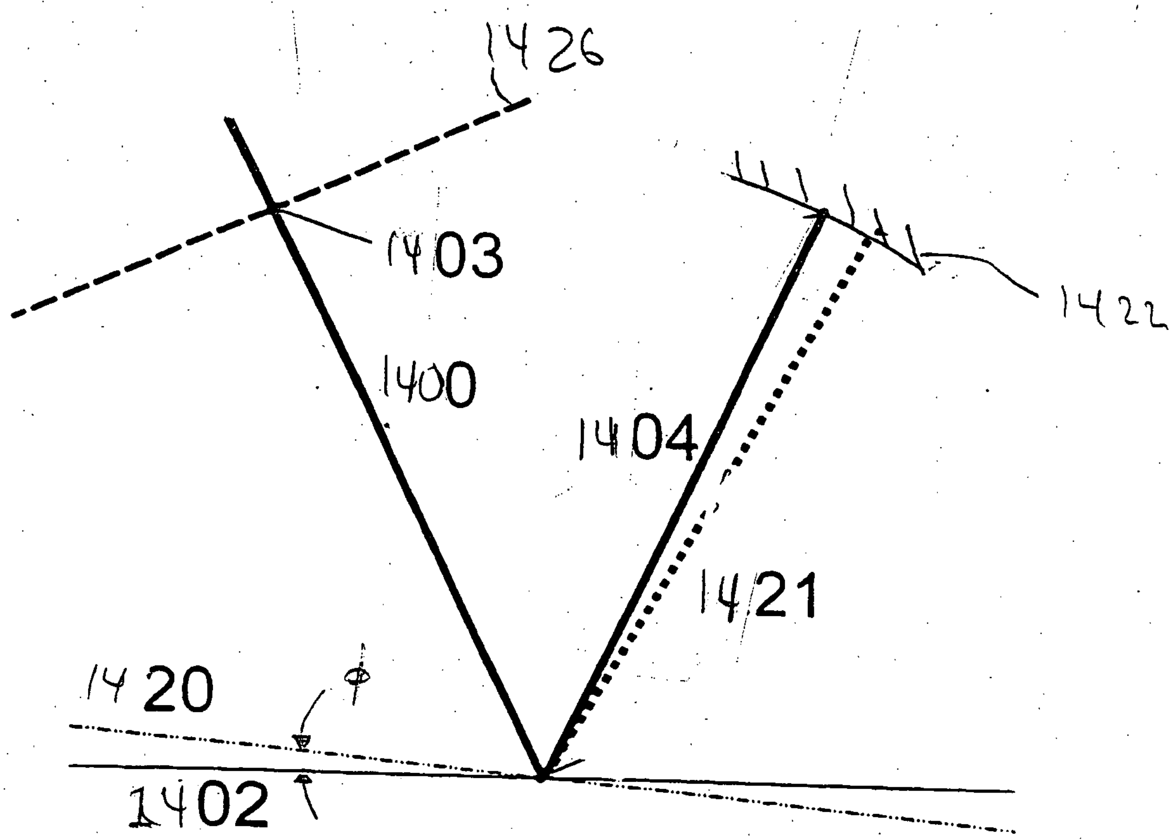


Figure 14

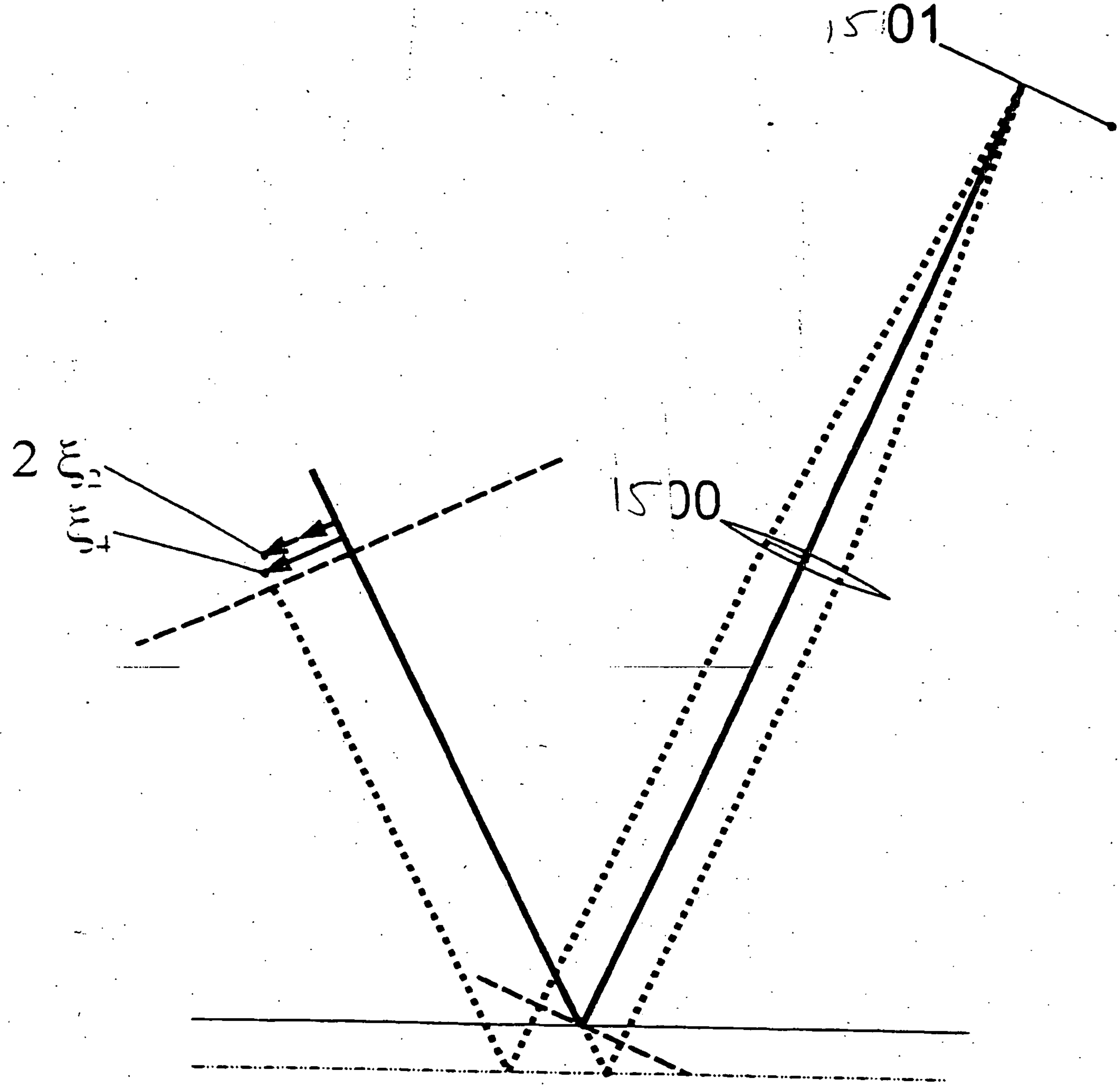


Figure 15

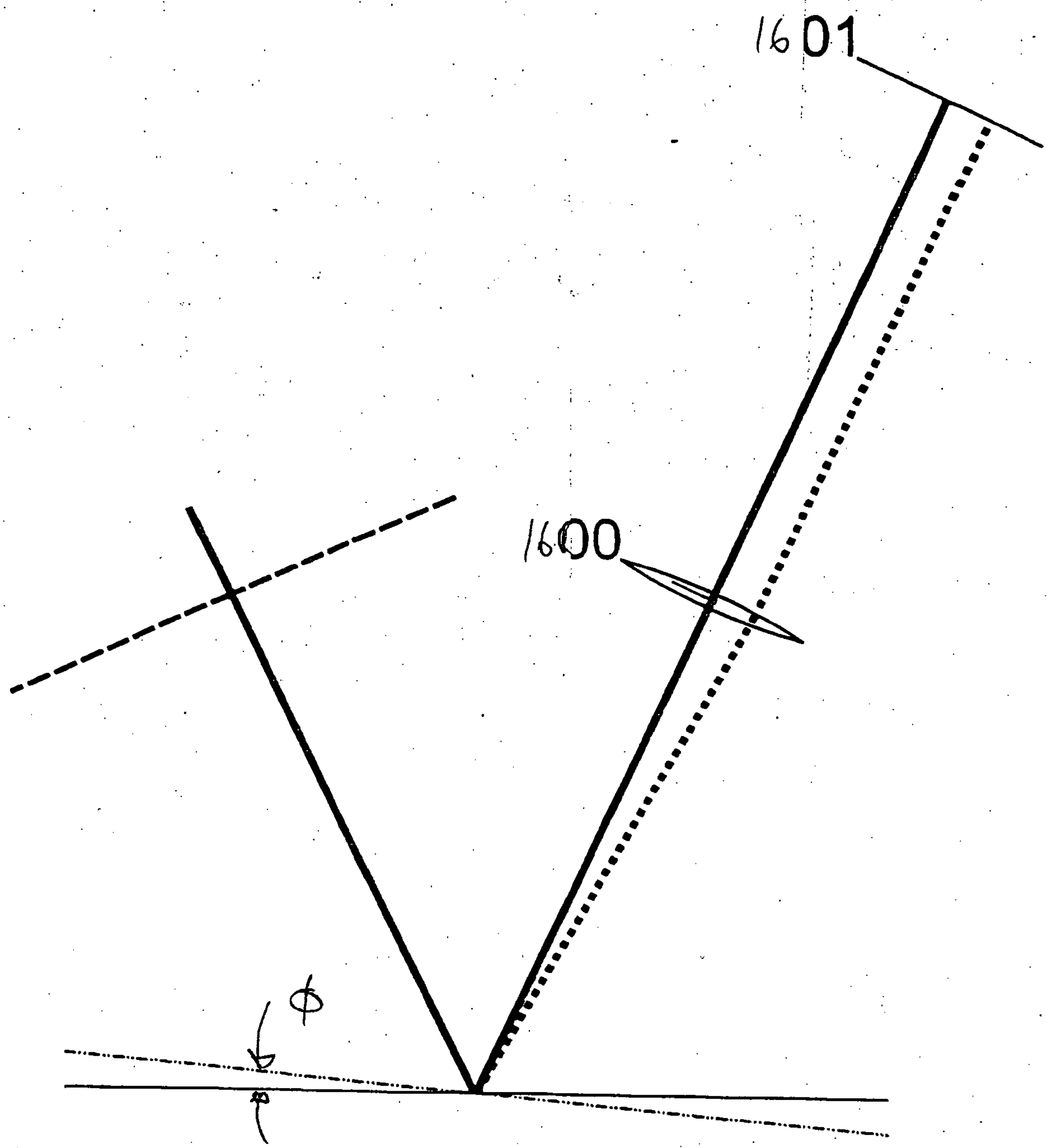
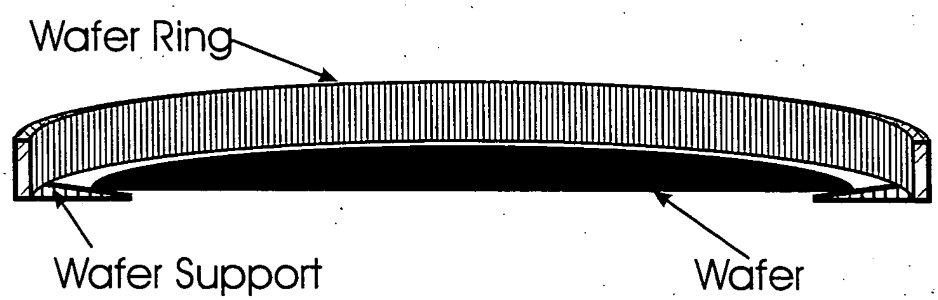
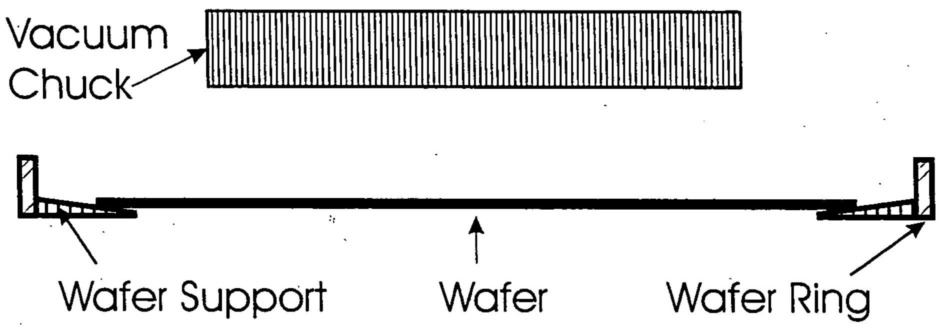


Figure 16



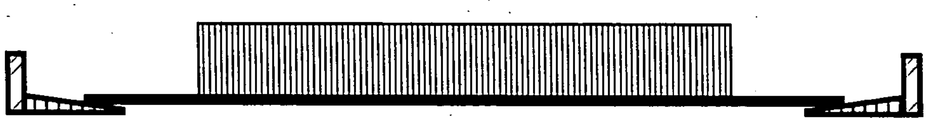
C.1.a

FIG 17



C.1.b

FIG 18

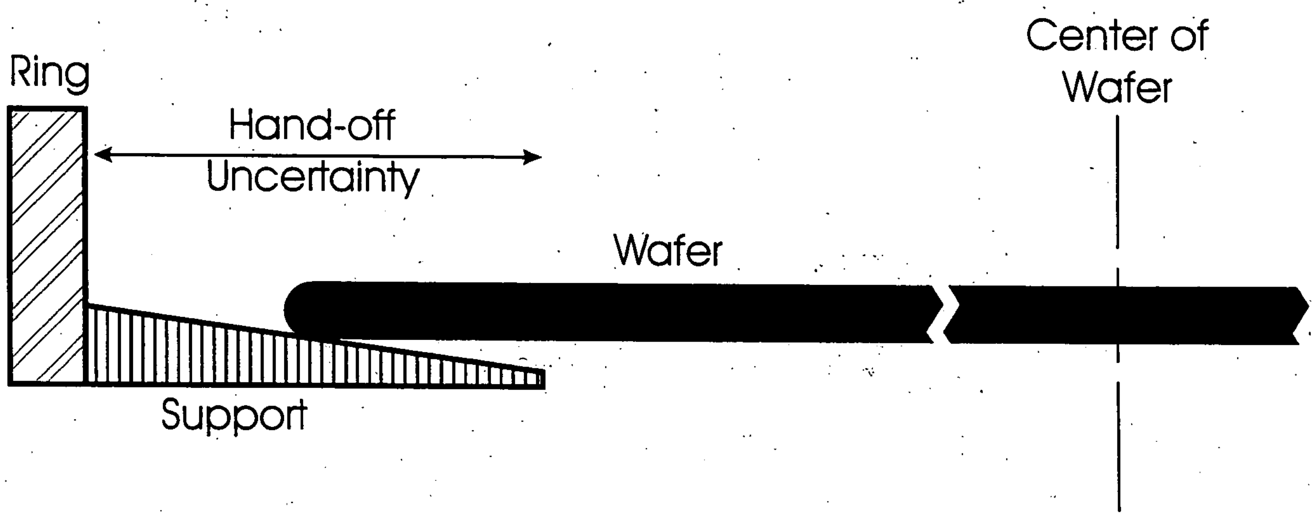


C.1.c

FIG 19

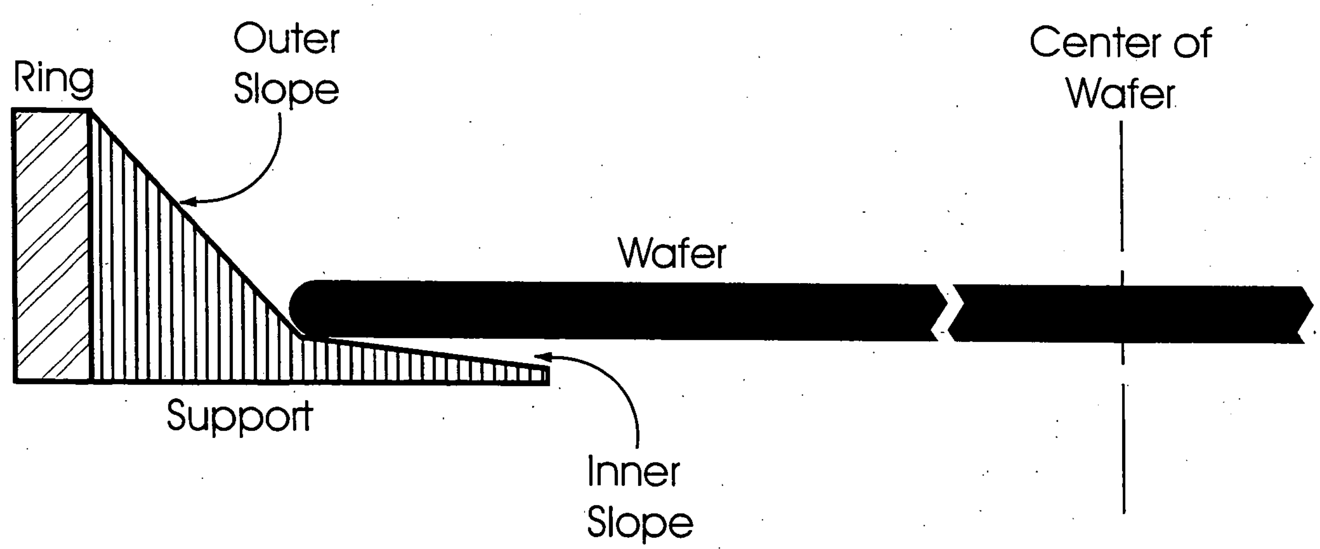
C.1.d

FIG. 20



C 2a

FIG 21

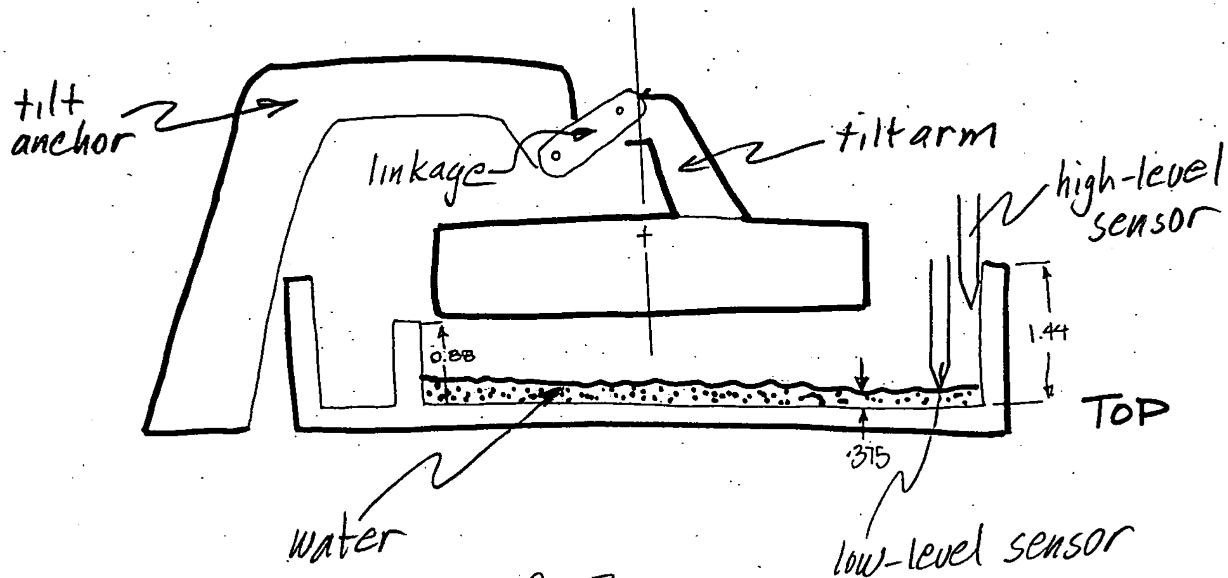


C 2b

FIG 22

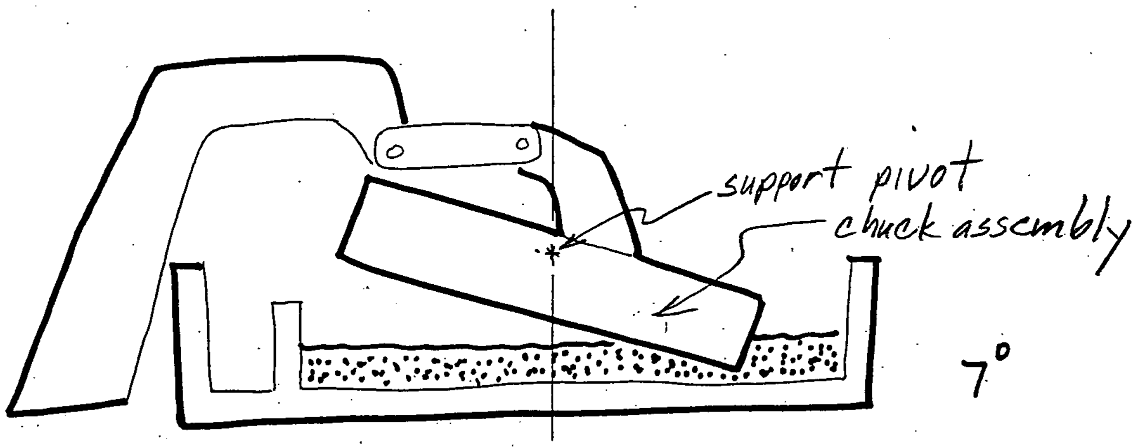
WATER LEVEL

TOTAL TRAVEL = 1.8 in



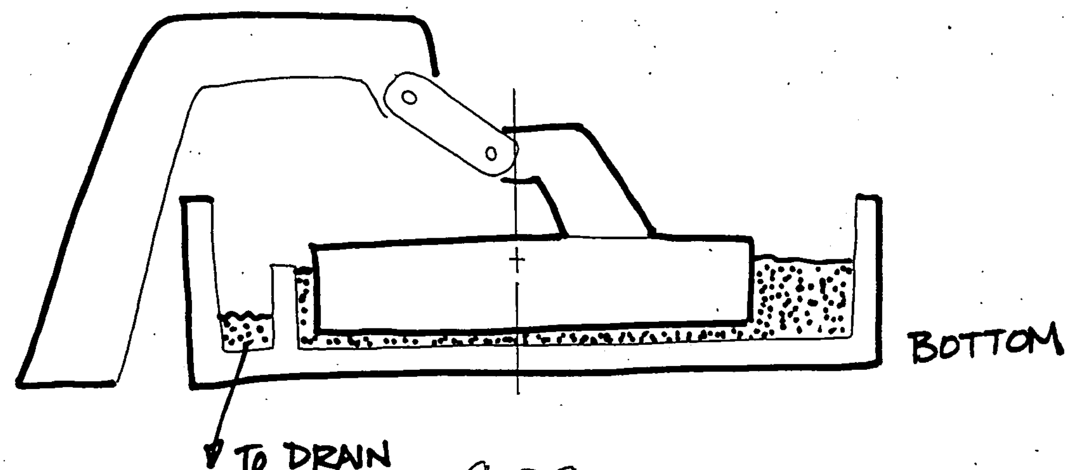
C 3 a

FIG 23



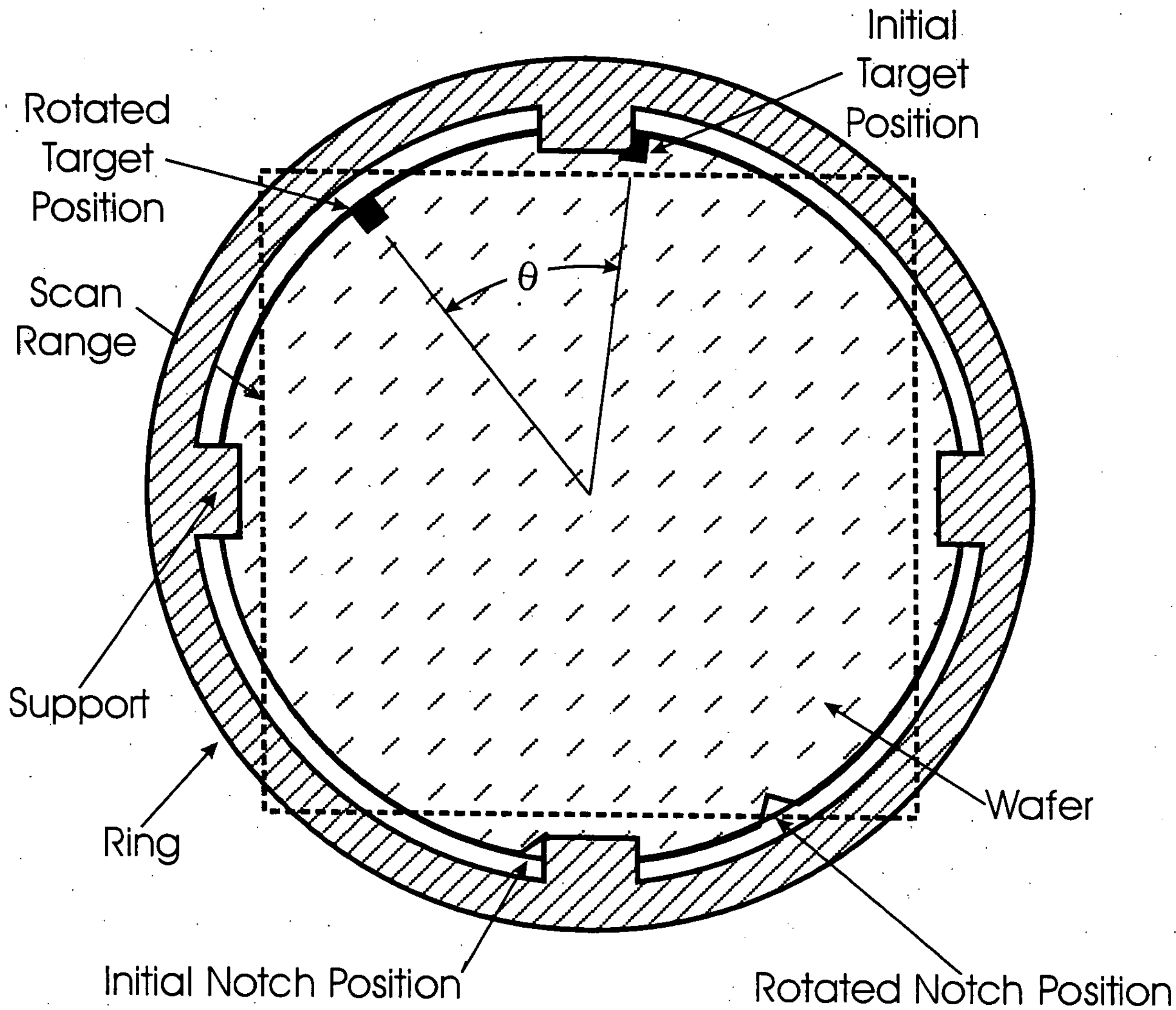
C 3 b

FIG 24



C 3 C

FIG 25


Initial
Target
Position
Rotated
Target
Position
θ
Scan
Range
Support
Ring
Wafer
Initial Notch Position
Rotated Notch Position

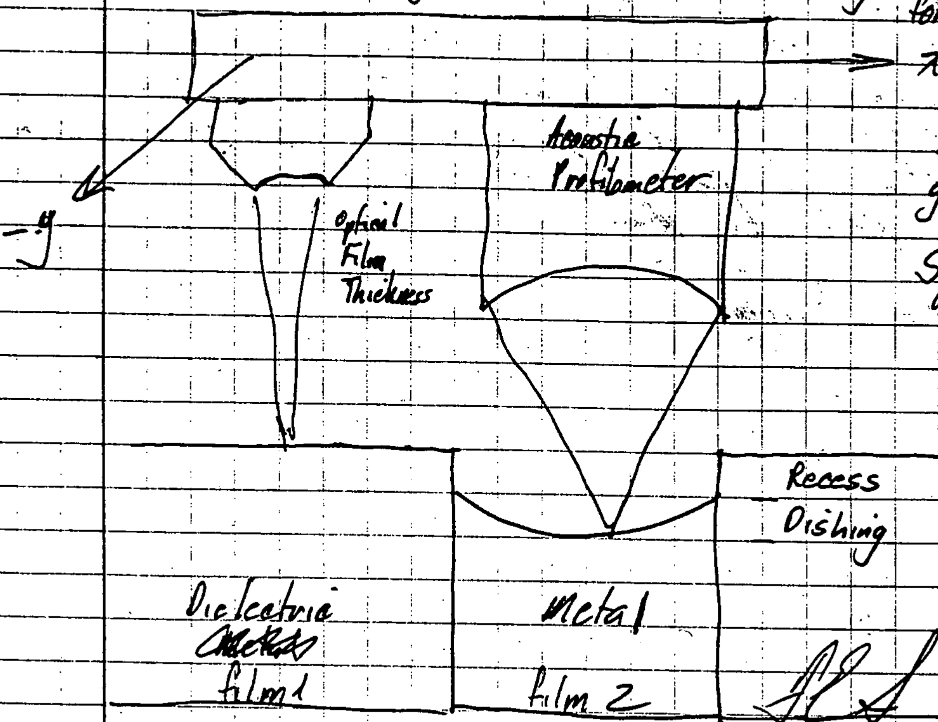
C 4

FIG 26

APPENDIX A

18 Nov 98

Need something for Cu. Profiling maybe. Could be useful for more than cu, anything, really.

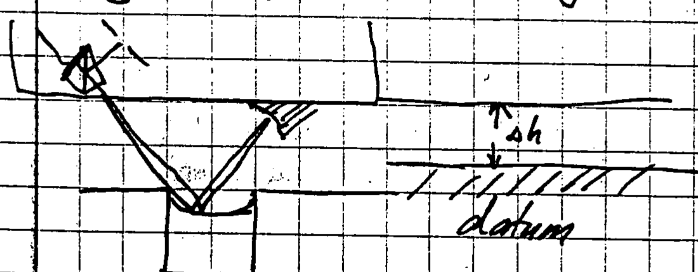


x-y stage needs to be good, maybe flexures

Squirter implementation possible

19 Nov 98 after discussion with Talat

An alternative would be to use the auto focus system, or an alternative ΔZ sensor, ~~optical or acoustic~~ as a profiler. In this case we would still need a very precise x-y, possibly a mini-x-y, or a datum, and some sort of reference indicator.



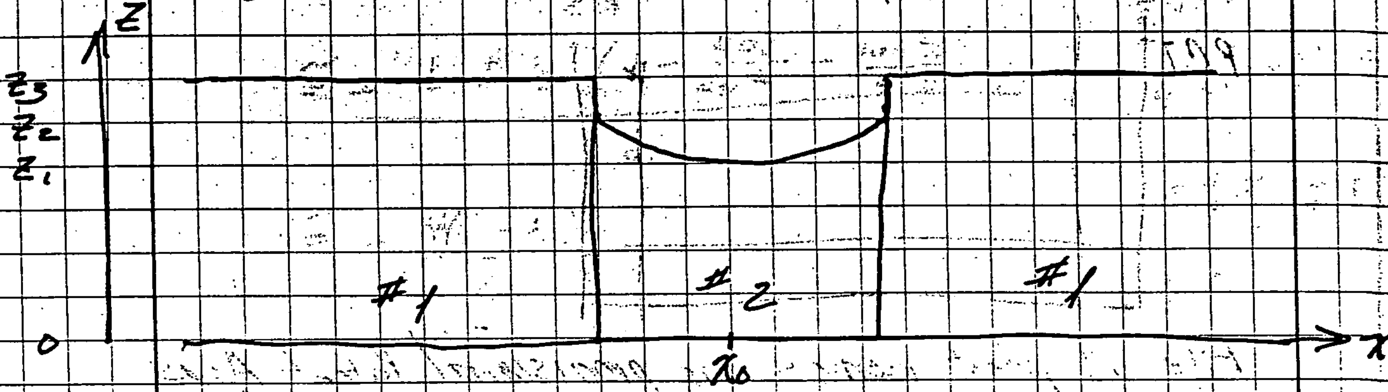
Either the acoustic or optical profilometers could be used for larger scale profiling, eg die-scale or wafer scale.

Read + Understood 3-7-99

A1

19 Nov 98

with reference to p. 42. Brian has previously suggested that it would be useful to combine an acoustic profilometer and optical thickness measurement.



An optical measurement of the film's thickness at x_0 gives an absolute number for $z_1 = \text{thickness}(x_0)$.
$= d(x_0)$

The acoustic measurement* gives a relative profile of the top surface $z(x)$. If we assume that the layer below is flat, we can calculate the thickness for "all" x as

$$d(x) = z(x) - z(x_0) + d(x_0).$$

& film #2 is transparent

If ~~the~~ film #1 is Cu, this is an acoustic-optic measurement of Cu thickness, which is, in general very difficult to measure.

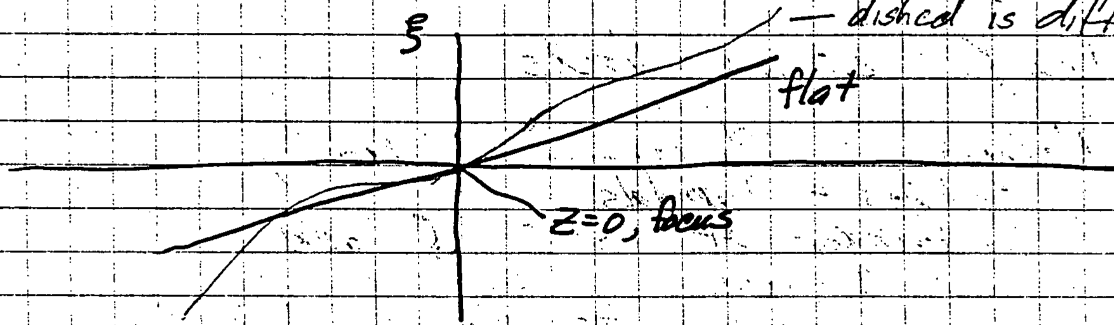
[signature]

* Page 10 shows ~~at~~ freq = 150 MHz spot size is 32 μm, depth ~~of~~ focus is 280 μm

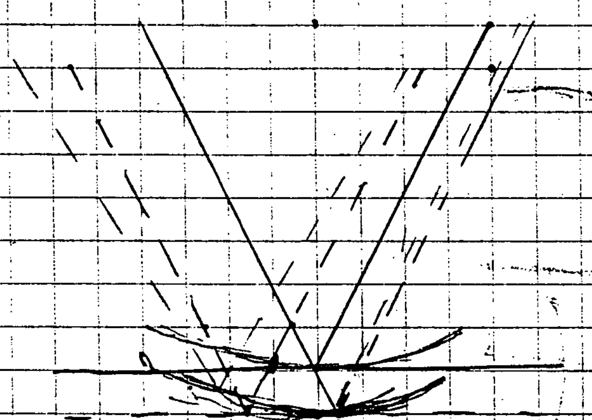
7 Dec 98

Dishing Measurement by controlled defocusing.

(A) For a flat surface, the displacement ξ of the autofocus beam on the detector is a known linear function of z



This will not be true if the surface (ie, metal pad) is dished, ~~this is bec~~ because the beams translate across the pad with defocus.



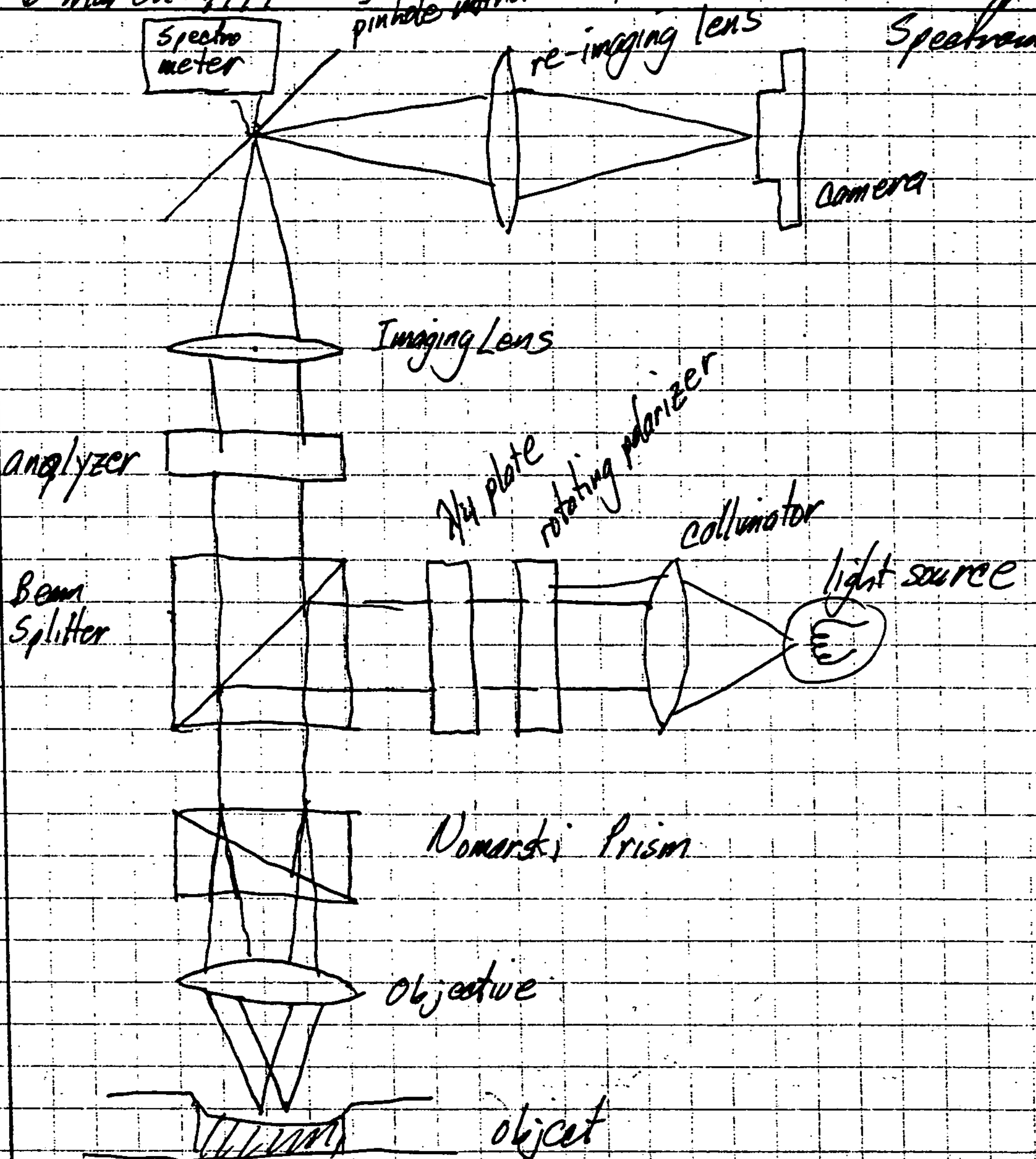
(B) Defocus should also affect the changes in $\Delta\xi$ differently for flat + dished reflectors.

[signature]

Read + Understood [signature] 12-7-98

A3

6 March 1999 Quantitive DIC Microscope with Spectrometer.



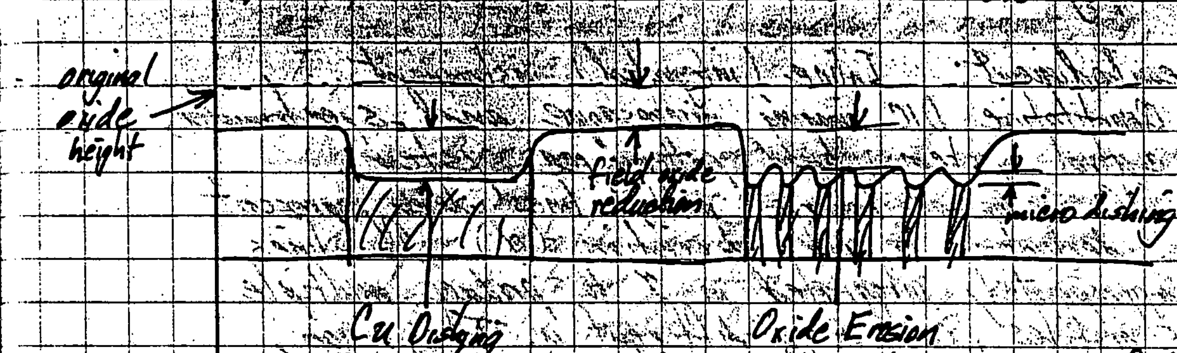
The basic idea is to combine a spectrometer and interferometer for optical profiling of a region having dissimilar materials. The interferometer measures the combined phase due to propagation (ie profile) and reflectivity (ie material). The spectrometer can characterize the materials to aid in determining the reflectivity phase. Subtracting the reflectivity phase from the interferometric phase yields the profile phase. In the example shown, the interferometer is a DIC with a rotating phase plate to make it quantitative. The spectrometer could be attached to the pinhole via a fiber, or directly

A4

Read + Understood 3-6-99

6 Mar 99

Problem: CMP leads to dish and erosion and field oxide reduction



all of which can degrade IC properties or cause failures.

Current Metrology: Contact profilers are slow, large, expensive and contact the wafer.

Solution: Optical Profilometry.

Types: Quantitative. DIC, Mirau, Michelson, etc
Imaging, scanning, N point (N=2, 3, etc)

Additional elements:
Vision system for locating profilometer fov in proper position on wafer via controlled positioning system.
Spectrometer to provide independent information about the local reflectivities of various points in the field of view, specifically to compensate for dissimilar materials and transparent media whose phases depend on thicknesses of underlying layers and/or lateral heterogeneities.
Position specific processing of spectroscopic and/or interferometric data to account for varying structures. Possibly assisted by vision system.
Ellipsometer replacing or in addition to spectrometer. Reflectivity characteri-

Venues:
Especially inline.
Possibly on fab floor. Faster than profiler and ~~guanteed~~ guaranteed non-destructive.
For Development.

[signature]

Read + Understood 3-~~6~~-99 [signature]

Next page →

6 Mar 99

from previous page.

Preferred embodiment: Inline (integrated) instrument with Quantitative DIC imaging microscope and spectrometer, motion control system, and pattern rec system.

* The DIC microscope returns multiple lines which represent phase derivative in one direction (x). The lines are appropriately integrated in x to produce multiple phase profiles, each at a different y. The vision system picks one profile which cross the feature of interest, FOI, ie, a dished Cu line, and assigns "material" types to points on the profile. The motion control system positions the spectrometer over a region where the reflected phase is unknown, ie, over a transparent stack or grating. The spectrometer characterizes the position and a phase algorithm calculates the phase. One all necessary ambiguous phases are resolved, the corrected profile phase is calculated from the phase profile and reflection phases, and finally the final profile is calculated, and the amount of dishing or erosion.

* First the vision system (pat rec) and motion control system position the field of view of the DIC microscope over a feature of interest (FOI).

~~Eaven~~ Even though the camera may have many pixels, eg 480 x 640, the DIC may have few pixels, eg 2 or three.

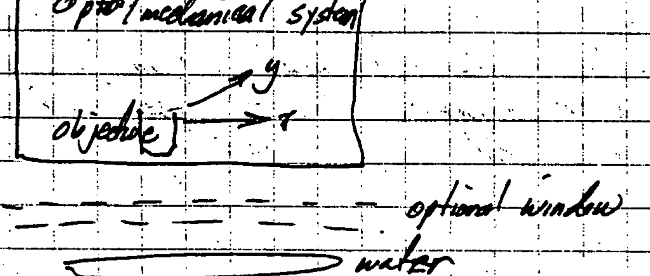
Read & Understood 3-6-99

A6

6 Mar 99

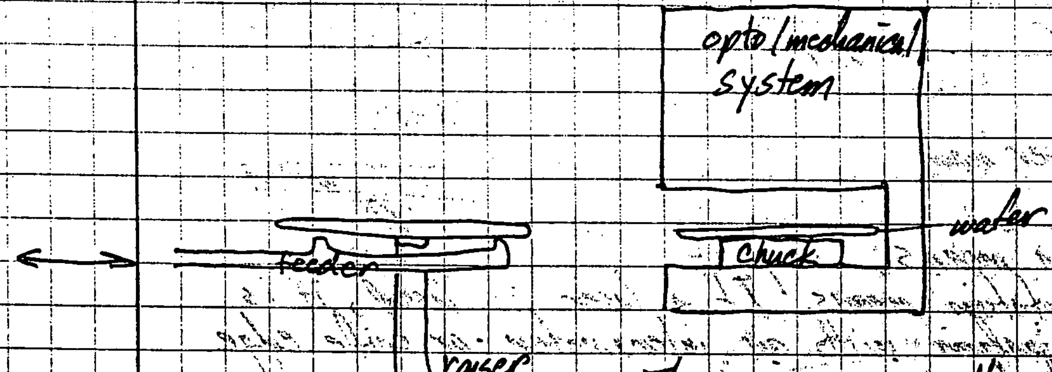
We talked to Elaura about integrating the ITM.

In some systems it may be advantageous to flip the ITM upside down, and to operate it dry.



The wafer can be held by a chuck, which preferably rotates.
The wafer could be held by a edge grip, which preferably rotates.
The window is optional.
The thickness and material(s) of the window (ie, "anti reflective" layers) can be optimized to allow optics designed for immersion to be used dry.

It may be advangeous to use a side loader



The raiser raises the wafer.
The feeder accepts the wafer from the raiser.
The feeder loads the wafer into the system, either directly onto the chuck or onto an inter loader.

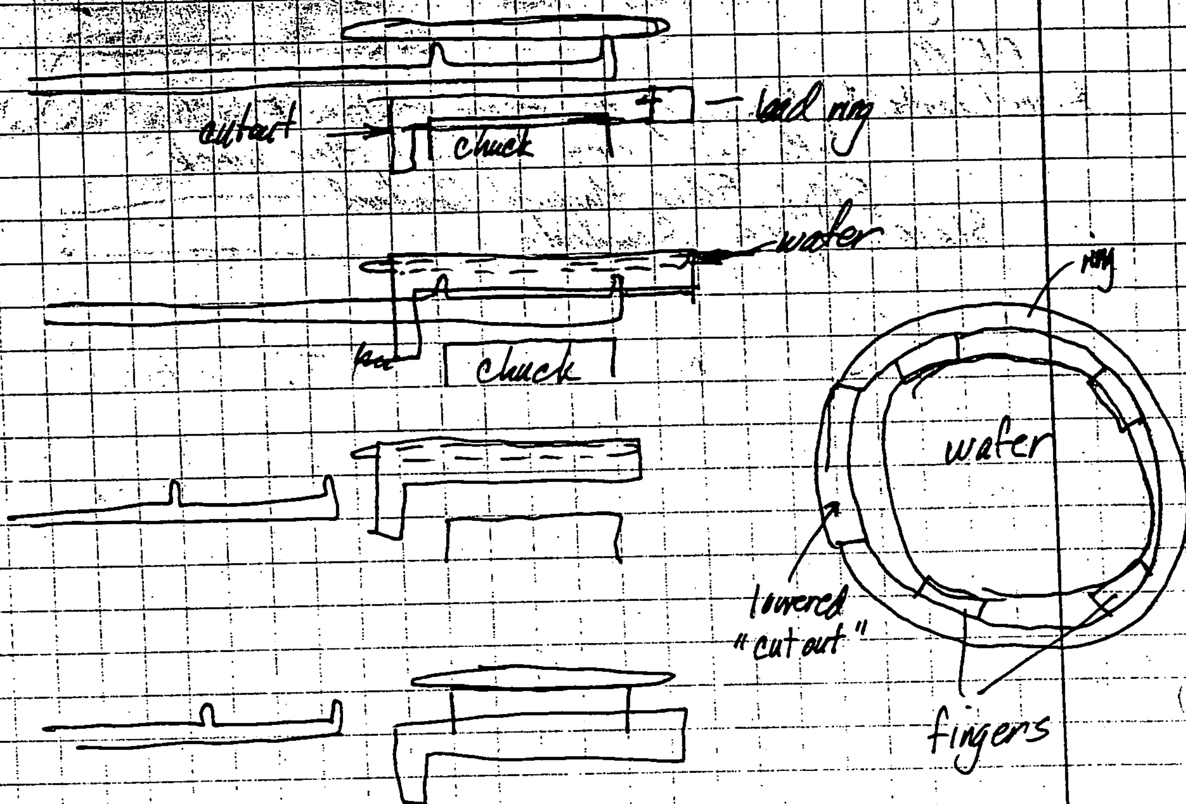
A7

cont.

Read + Understood 8-6-99

6 Mar 99 cont

Sensys' current safety ring with three positions is easily modified to accept the wafer from a feeder w/o "Z".

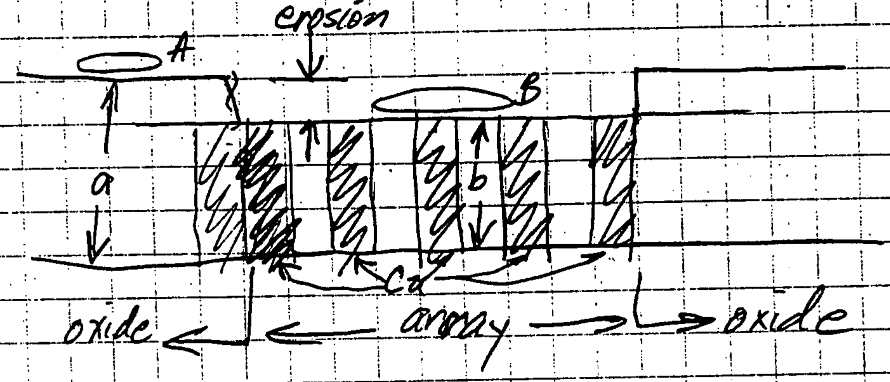


Only two positions necessary.

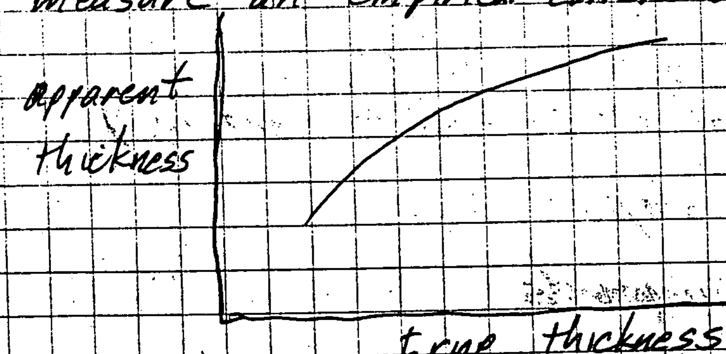
Read + Understood 3-6-99

10 Mar 99

Reflectometer measurement of erosion



Erosion is the difference of field-oxide thickness a and array oxide thickness b. The goal is to measure a and b with optical measurements with spots A + B. The problem is that the array's copper lines perturb the standard optical thin film measurement made be either reflectometry or ellipsometry. The basic idea is to make a valid thickness measurement of b by empirical or theoretical means. In the first case if the copper lines make a rather slight perturbation one could measure an empirical calibration curve



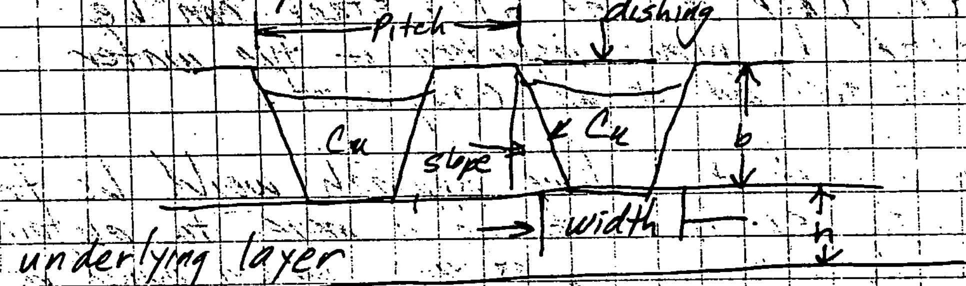
from a set of samples. The calibration curve is presumed to be a function of the details of the array: pitch, density, dishing, etc. As long as the curve is monotonic, it can be unambiguously mapped to measure ~~value~~ thickness b of other arrays of the same type

cont.

A9

10 Mar 99
cont.

~~Another~~ The previous approach implicitly treats the array as a effective homogeneous layer. An alternative is to use a model, such as rigorous coupled mode theory, to model the optical response of the array, and use the model in an optimization procedure to invert for thickness b, and possibly other array parameters. For example, fixed parameter might be pitch, array N+K functions, N+K of underlying layer ~~phase~~. ~~Inverted parameters~~ and array slope and line width



The inverted parameters might by oxide thickness b, and thickness of the underlying layer h. Other parameterizations are possible. In this case the array is being ~~the~~ treated as a periodic grating.

Both approaches assume that the array pitch is smaller than the spot size and that a is easily measured using standard techniques. If the pitch is larger than the spot size, b can also be measured with standard techniques.

Fred C Stanke

11 Mar 99

Another mode for ~~oper~~ operating the ITM is to collect data on the fly as the objective scans the wafer. The idea is to get a better sampling of points on the wafer, with spectral information. The spectrum may or may not be as densely sampled. The integration time might be shorter to allow more points to be sampled.

One application of such date would be to look for small amounts of a remaining film that should have been removed. Eg. there are reports that remaining oxide on the nitride after CMP of an STI stack can be detected by human inspection of the wafer without the aid of any equipment.

A variant of the above approach would be to sample the spectrum during a move to obtain a single average spectrum, which could be processed to detect color anomalies.

[signature]

SENSYS ITM SPECIFICATIONS

Product Attributes	**Specification/Functionality**	**Benefits**
Measurement type	Wet wafer measurements	Quick feedback loop Ability to rework wafer
Minimum Film Thickness	<30 nm	Significantly improved robustness for STI applications.
Accuracy	1 nm (< 100 nm films) 1% (≥ 100 nm films)	Improved process control.
Precision (1σ)	0.1%	Improved process control.
Spot size	10μ x 10μ	Greater flexibility and extendibility.
Measurement Speed (5 points/wafer)	120 wafers/hour	Higher throughput results in OEE, COO improvement, allows more uniformity data.
Measurement Locations	Any number of die on 200mm wafer. Multiple sites per die.	Flexibility in determining uniformity, process capability.
Measurements on multiple types of film stacks within a die	Yes.	Greater Flexibility.
Pattern Recognition	Fast, direct & robust. Any wafer orientation.	Improved throughput and ease of use.
Centering and Notch Alignment	Yes.	Measurements on unpatterned wafers (e.g. point-to-point subtraction for pre and post measurements), ease of set-up.
Chucking	Vacuum chucking with wafer rotation.	Diameter scans with 0mm edge exclusion in any direction.
Die Size Estimator	Determine die size for any unknown design.	Ease of set-up.
Internal Referencing	Yes.	Far superior stability and reduced calibration frequency.
Data Display & Analysis	Advanced, including trending capabilities.	Improved process control.
GUI display on CMP tool	Yes.	Improved ease of use, need for a separate computer cart eliminated.
Lamp location, replacement	Remote. Easy to replace.	Improved uptime, ease of use. Higher reliability.

SENSYS INTEGRATED METROLOGY SYSTEM
COMPETITIVE ADVANTAGES

Product Attributes	Nova 420	Sensys Offering	Sensys Competitive Advantage
Thin films Measurement	80 nm	30 nm	Significantly improved robustness for STI applications
Accuracy (< 100 nm films)	Not specified	1 nm	Improved process control
Precision (1σ)	0.25%	0.1%	Improved process control
Spot size	15μ x 15μ	10μ x 10μ	Greater flexibility and extendibility
Measurement Speed (5 points/wafer)	45 sec/wafer	20 sec/wafer	Higher throughput results in OEE, CoO improvement, allows more uniformity data
Chucking	None	Backside, vacuum	Diameter scans with 0 mm edge exclusion. Flat wafer surface leads to higher throughput, performance.
Centering & notch alignment	No	Yes	Higher throughput, diameter scans, improved ease of use
Data Analysis	Basic	Advanced	Improved process control
Measurements on multiple stacks within a die	No	Yes	Greater Flexibility
Pattern Recognition	Slow, searching	Fast, direct & robust.	Improved throughput and ease of use
GUI display on CMP tool	No	Yes	Improved ease of use, need for computer cart eliminated.

SENSYS

A1

SENSYS INTEGRATED METROLOGY SYSTEM COMPETITIVE ADVANTAGES

- **Improved production efficiency**

	Sensys Advantage	**Nova 420 Disadvantage**
Fewer false alarms	Reliable, statistically robust data leads to fewer false alarms during production.	More false alarms are likely during production due to less reliable data.
Higher Throughput	Higher measurement speed ensures CMP tool throughput is not limited during production.	Lower throughput may limit CMP tool throughput during production.
Higher Availability	Higher system reliability ensures CMP tool availability is not affected.	Lower system reliability may negatively impact CMP tool uptime.

SENSYS

SENSYS INTEGRATED METROLOGY SYSTEM COMPETITIVE ADVANTAGES

1. CoO IMPROVEMENT ADVANTAGE THROUGH OEE IMPROVEMENT

OEE (Overall Equipment Effectiveness) of a CMP tool is a measure of its productivity, and represents the percentage of the time that the tool is running production wafers in the intended manner.

CMP Tool OEE improvement advantage over Nova 420 is achieved by

Improved reduction in set up time

	Sensys Advantage	**Nova 420 Disadvantage**
Reduction in time required for teaching	Robust & fast pattern recognition, small spot size enables a wide choice of patterns and fast teaching.	Slow, searching pattern recognition results in slow teaching.
Fewer test/monitor wafer runs	High accuracy & precision, diameter scan capability, measurement of multiple stacks within a die enable statistically robust data resulting in fewer runs	Relatively low accuracy & precision, lack of diameter scan capability and lack of multiple stacks measurement capability results in less robust data and more wafer runs.
Higher throughput	Higher measurement speed results in set up runs completed in a shorter time	Lower measurement speed, if it limits CMP tool throughput, results in a longer time.

SENSYS

SENSYS INTEGRATED METROLOGY SYSTEM COMPETITIVE ADVANTAGES

2.CMP TOOL CoO IMPROVEMENT ADVANTAGE THROUGH COST REDUCTION

	Sensys Advantage	Nova 420 Disadvantage
Higher throughput	Higher measurement speed ensures CMP tool throughput is not limited during production. Lowers the cost of processing production wafers.	Limitation on CMP tool throughput will result in a lower CoO improvement.
No added footprint	Integrated computer eliminates cart in chase/fab area.	Cart required for computer.
Fewer test/monitor/send ahead wafers	Results in reduced wafer costs.	More wafers result in higher costs.
Fewer process scraps, higher yields	Enabled by reliable metrology data.	Less reliable data
Lower maintenance costs	Higher system reliability ensures low maintenance costs while not affecting CMP tool availability	Lower system reliability leads to higher maintenance costs. CMP tool availability may be negatively impacted.

SENSYS

A16

1) Purpose.

This document briefly summarizes the architecture of the "dROPzONE", the wafer handling subsystem of the Integrated Thickness Monitor (ITM). It covers descriptions of the functional subsystems.

2) Scope.

The scope of this document is to disclose the concepts and advantages of transferring the wafer from a horizontal orientation, at the wafer load/unload position, to a vertical orientation, at the wafer measurement position. The intended audience is the principals of Sensys Instruments and approved consultants, contractors, and legal advisors.

3) System Overview.

The dROPzONE is the wafer handling subsystem of the ITM, which consists of the mechanisms that transport the wafer from the load position, to the measurement position, and back to the load position for unloading.

There are six basic subsystems of the dROPzONE:

1) A load/unload port, which also includes a wafer centering mechanism and a bearing & drive system to pivot the load port from horizontal to vertical.
2) A notch aligner, consisting of a rotating vacuum chuck, an optical notch detector, and a drive system to rotate the chuck.
3) A transport carriage, which consists of the rotating vacuum chuck of item 2) and a "safety net" to catch the wafer in the event of vacuum loss.
4) A vertically oriented bearing, rail, and drive system, which transfers the "carriage" from the notch aligner position (in air) to the measurement position (in de-ionized (DI) water).
5) A DI water tank with a liquid level sensor and electronically controlled shut-off valve.
6) A vertically oriented quartz window, which allows the components of the optical metrology to remain "dry" while the wafer is submerged.

The dROPzONE receives the wafer device-side down from the CMP Tool's robot. Once loaded, the wafer is gently pushed against two reference pins to mechanically center it. With the wafer secured, the load port pivots upwards to transfer the wafer onto a vertically-oriented vacuum chuck. A vacuum chuck constrains the wafers into a flat plane and allows for rotary motion. While a reflective sensor looks for the notch at the circumference, a capstan drive rotates the vacuum chuck. Once located, the notch may be rotated to a user-defined location.

When the carriage (vacuum chuck) is lowered into the DI water tank, it leaves behind the capstan drive of the notch aligner. The carriage is stopped at the measurement position by hard stops. Hard stops improve positional repeatability at this critical location.

To unload the wafer, reverse the process leaving out the notch alignment step.

A17

4.1) The dROPzONE has the ability to orient a patterned, or unpatterned, wafer with respect to the notch and center of the wafer.

4.2) The dROPzONE lowers the wafer into the DI water with the wafer in the vertical orientation. This minimizes air bubbles adhering to the device-side of the wafer. Bubbles can adversely affect pattern recognition and the optical metrology.

4.3) The dROPzONE incorporates a quartz window in the vertical orientation. This minimizes sedimentation of contaminates in the DI water onto the window.

4.4) The dROPzONE raises the wafer out of the DI water with the wafer in the vertical orientation. This maximizes drainage of DI water from the wafer surface.

4.5) The dROPzONE holds the wafer with a vacuum chuck during measurements. This flattens out the wafer from planar deviations; and allows for "zero edge exclusion", which means allows you to measure out to the edge.

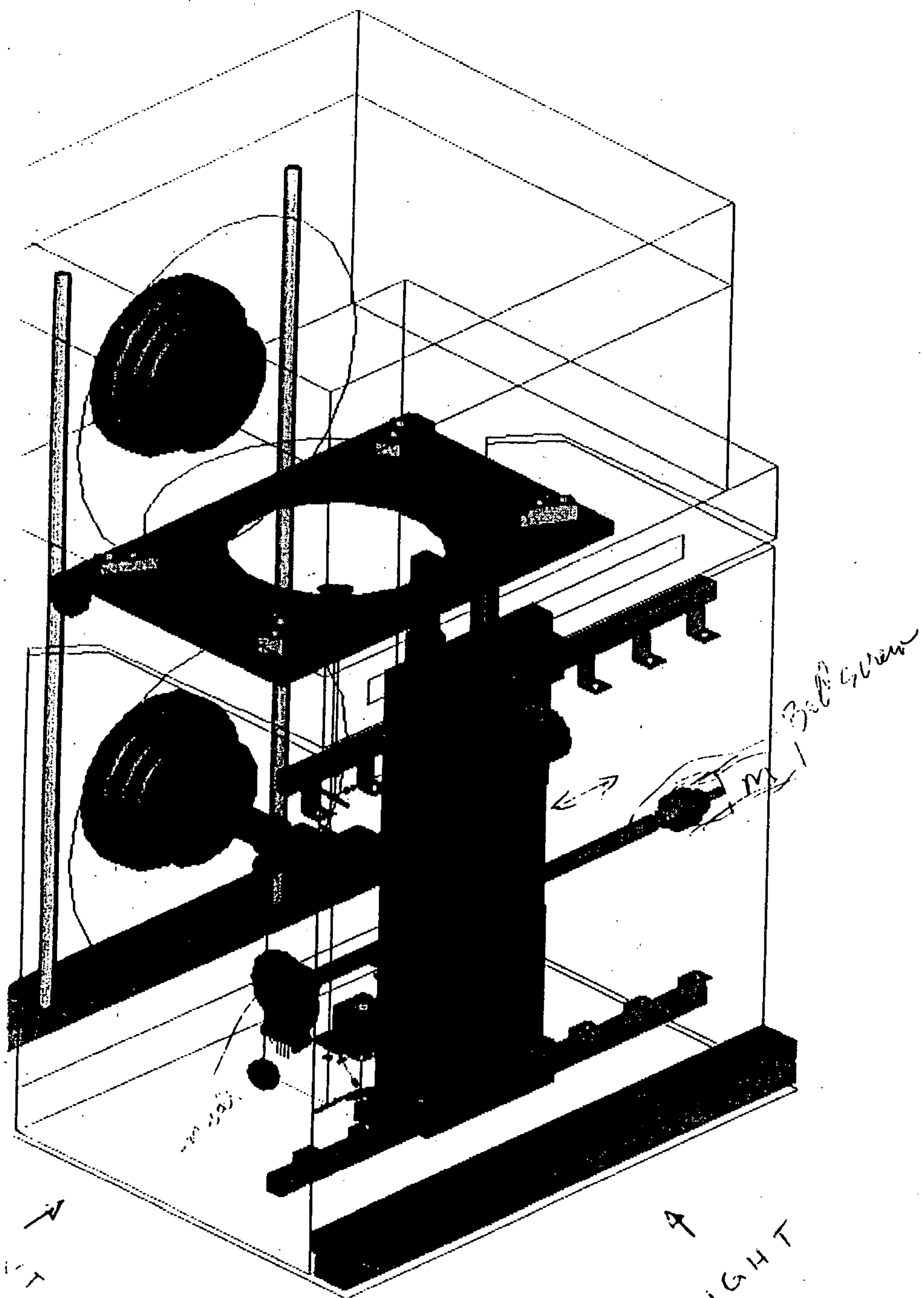
5) Definitions.

5.1) The Wafer Handling Subsystem refers to the portion of the ITM that manipulates the wafer. It performs four functions:
a) Accepts the wafer from the CMP tool (load).
b) Performs notch alignment.
c) Presents the wafer to the measurement optics.
d) Presents the wafer to the CMP tool after completion of metrology cycle (unload).

5.2) The Integrated Thickness Monitor (ITM) is an in-line thin film metrology instrument for monitoring the process of Chemical Mechanical Polishing (CMP) tools. It is to be installed within the CMP tool and operated as an integral part of the CMP tool.

5.3) Notch alignment refers to the process of determining the angular location of the wafer's notch with respect to the center of the wafer.

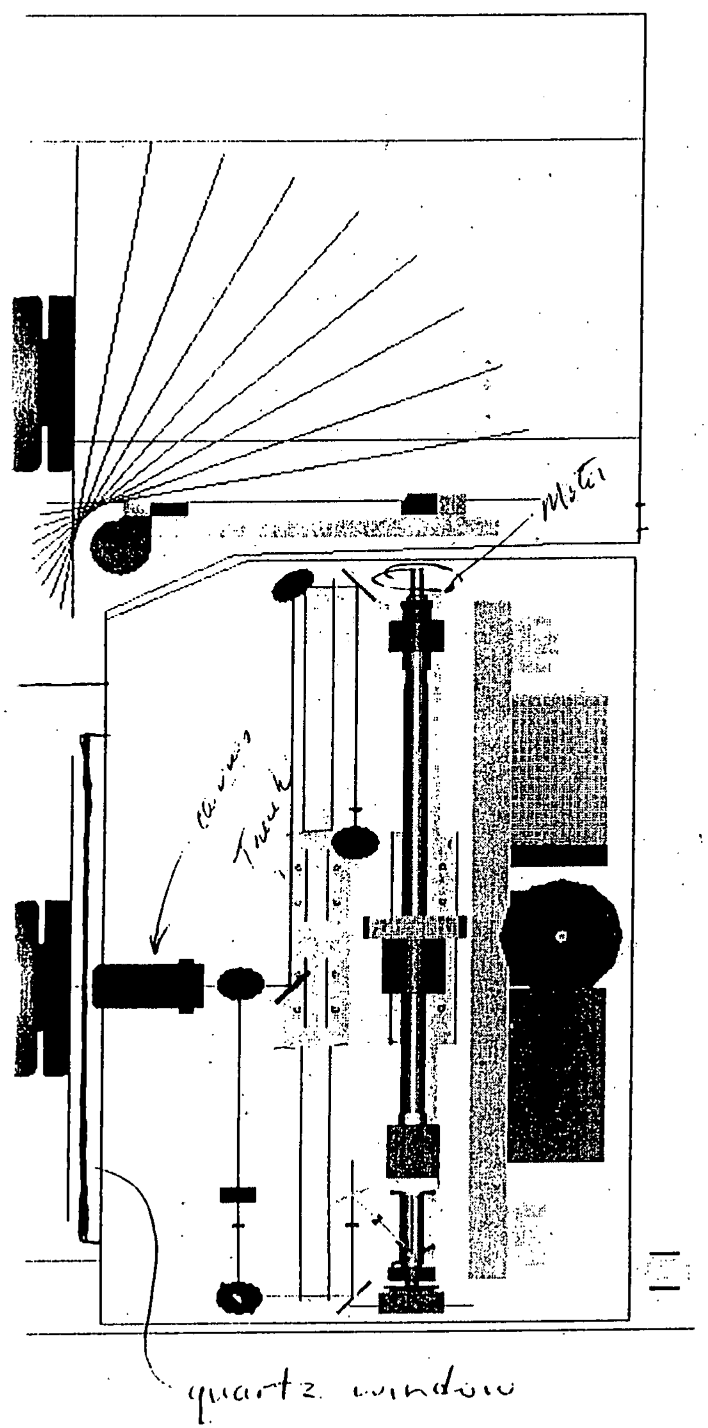
5.4) DI water is filtered de-ionized water. A key factor the ITM depends on is the physical property of the absence of air (oxygen) in DI water. This is extremely important in that if there were a substantial amount of oxygen dissolved in the DI water, bubbles would form on the measurement window and wafer surfaces.



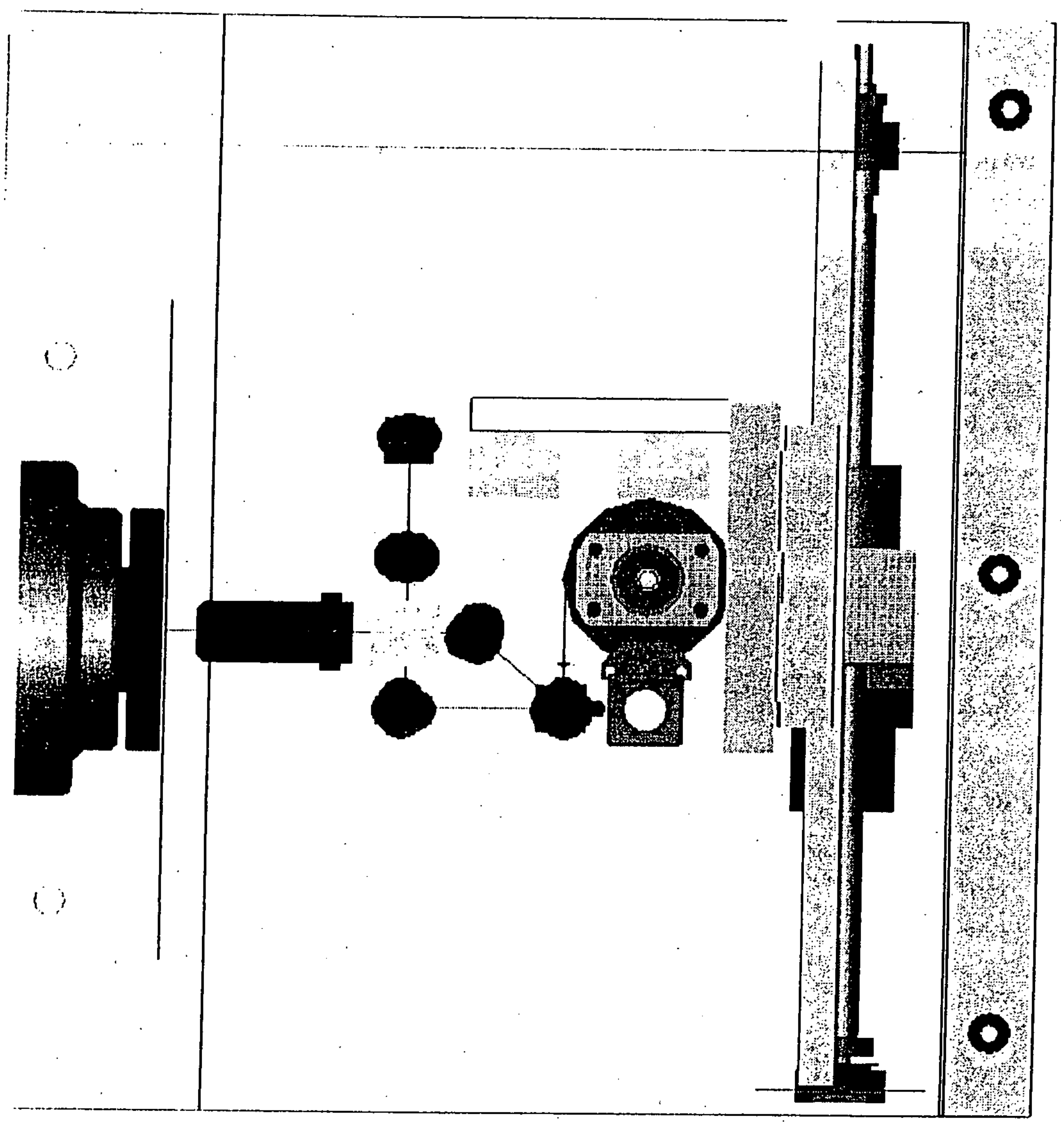
Isometric View

A19

FRONT VIEW



A20



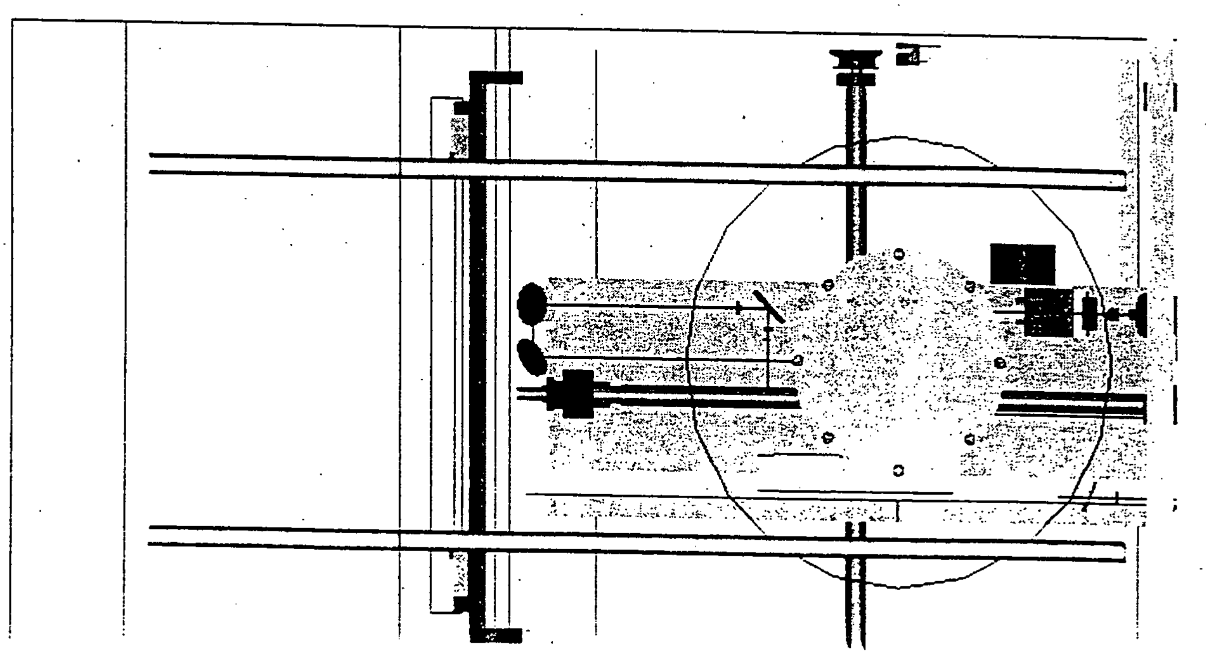
← RIGHT

↑

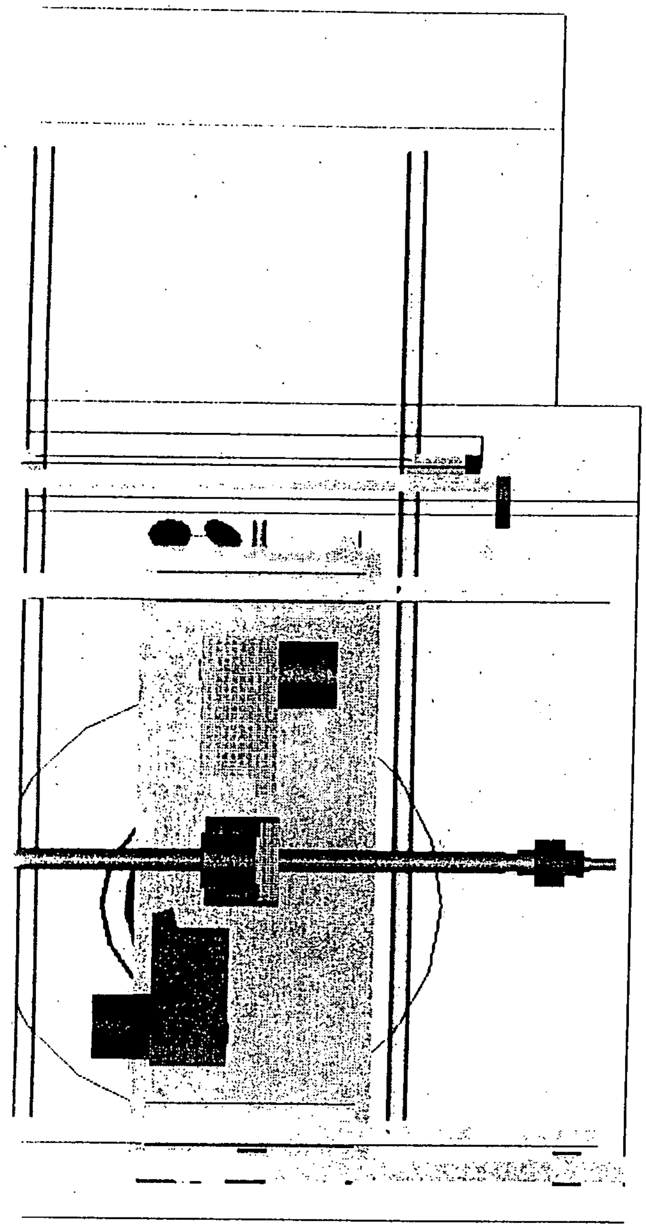
FRONT

Top View

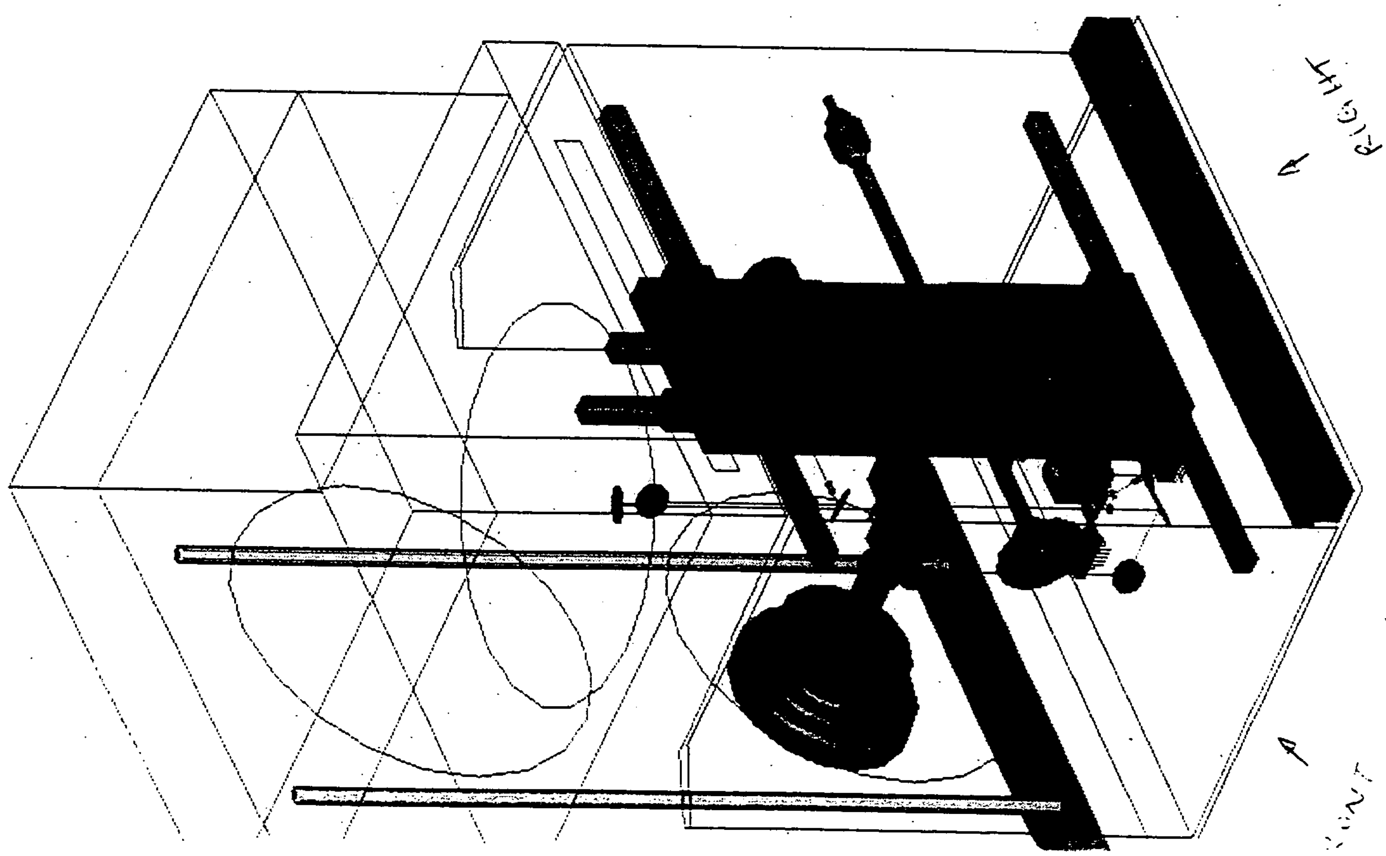
Left View



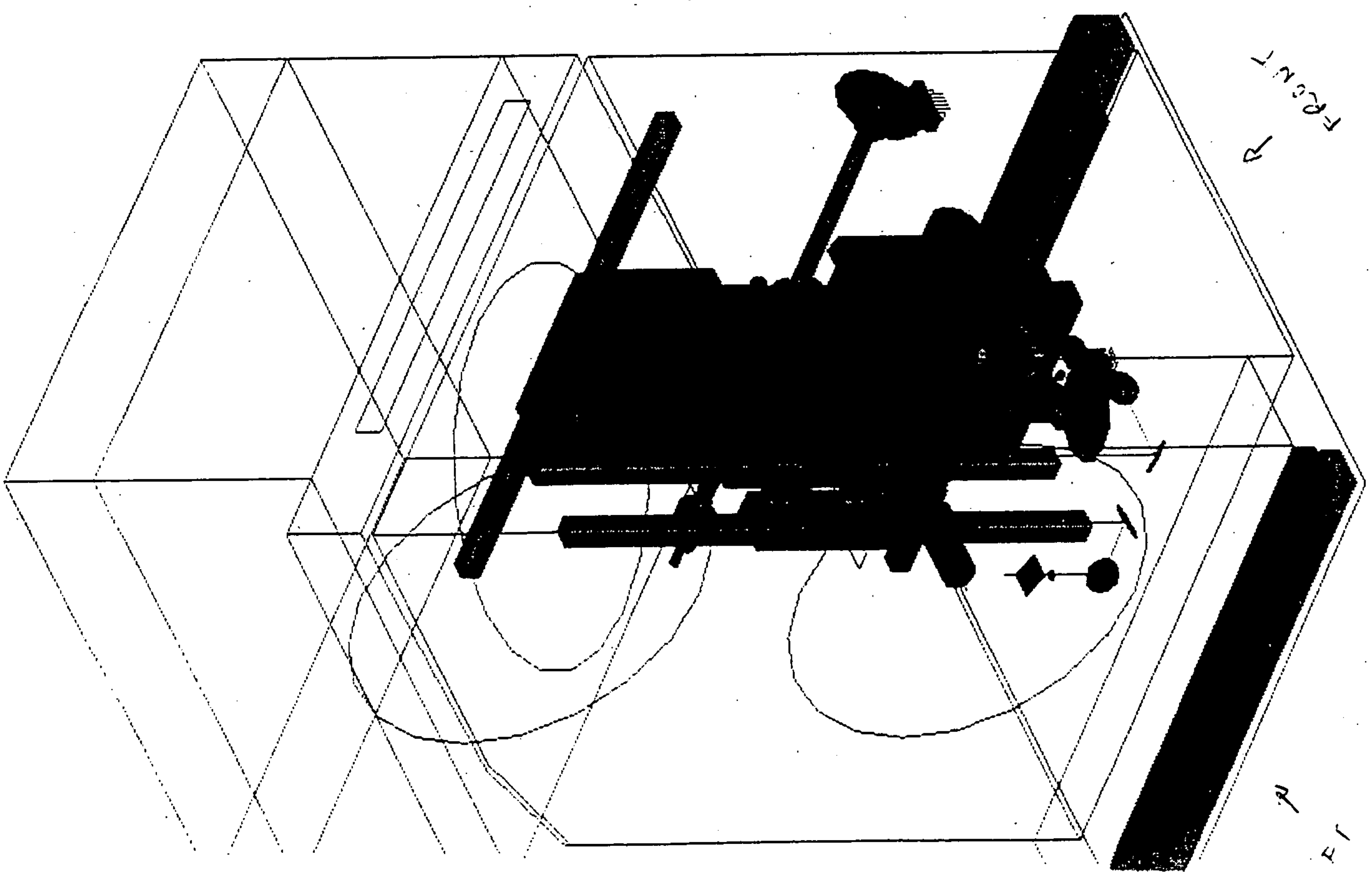
A22



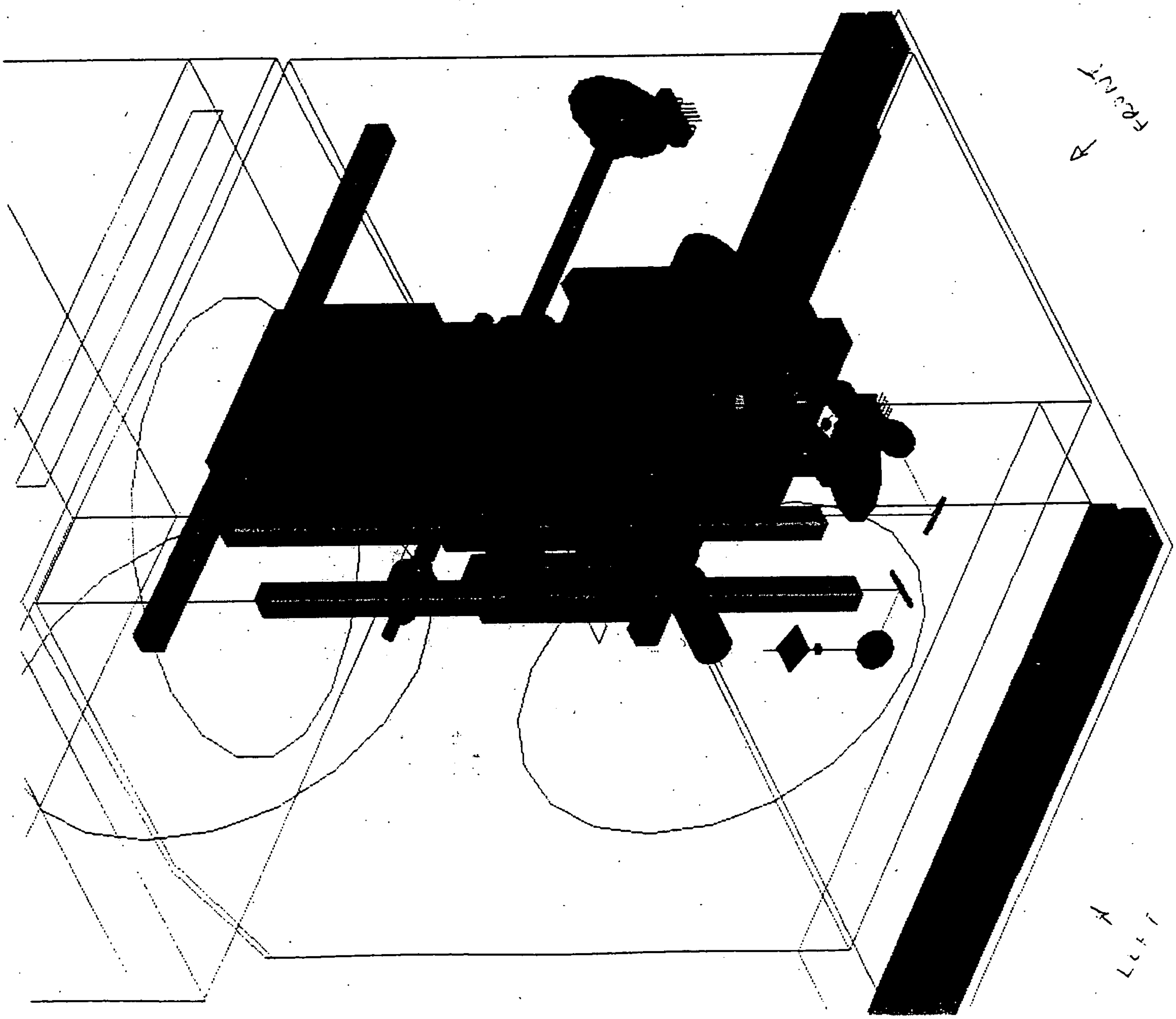
Right View



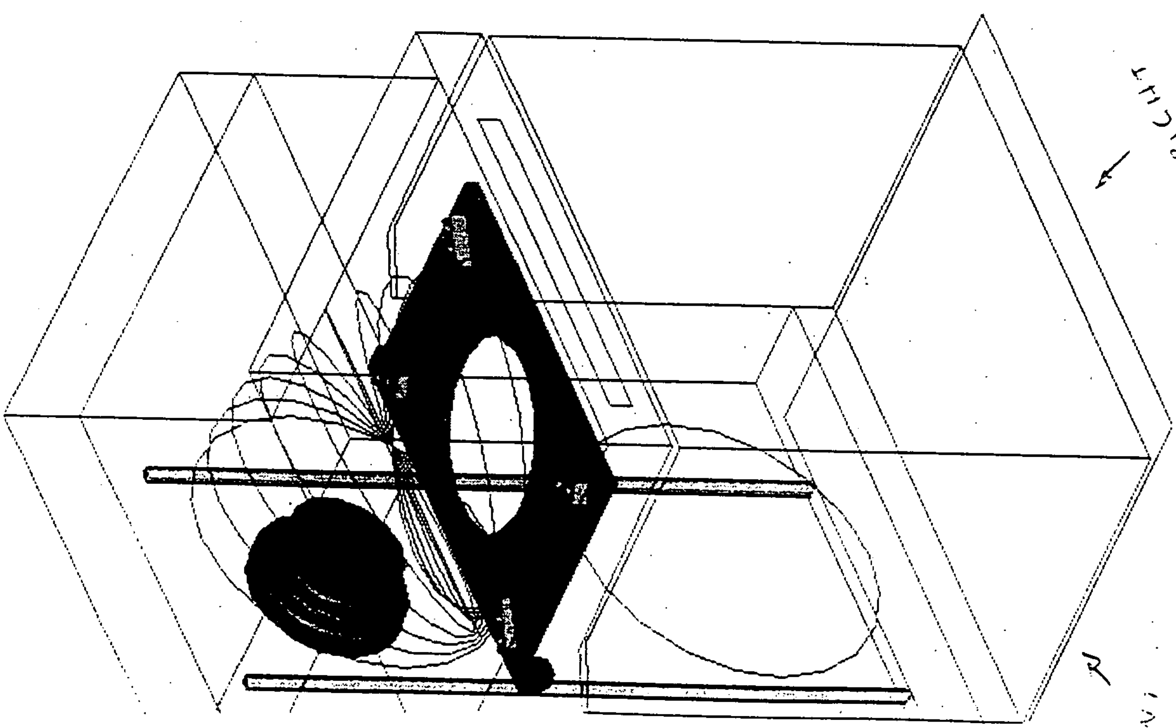
A 24



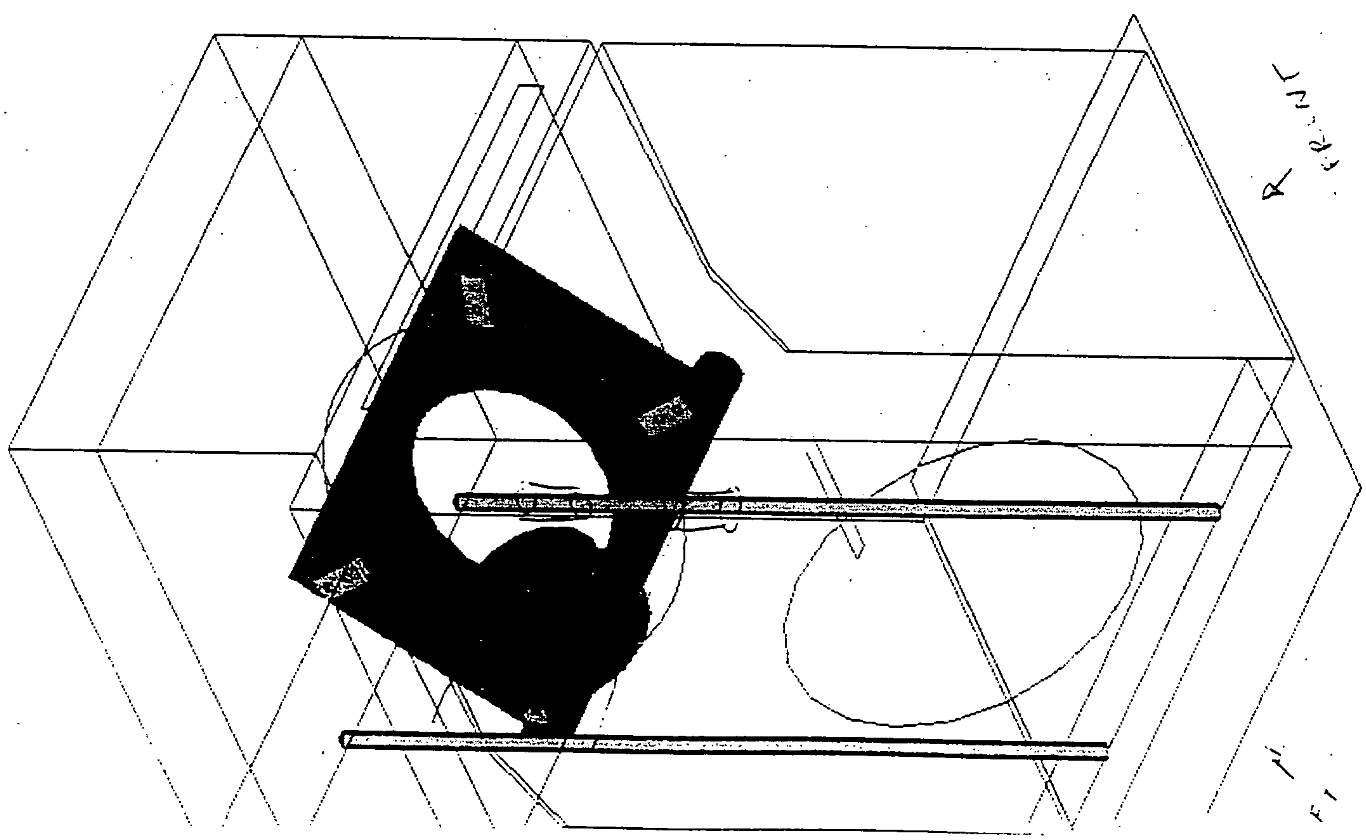
A25



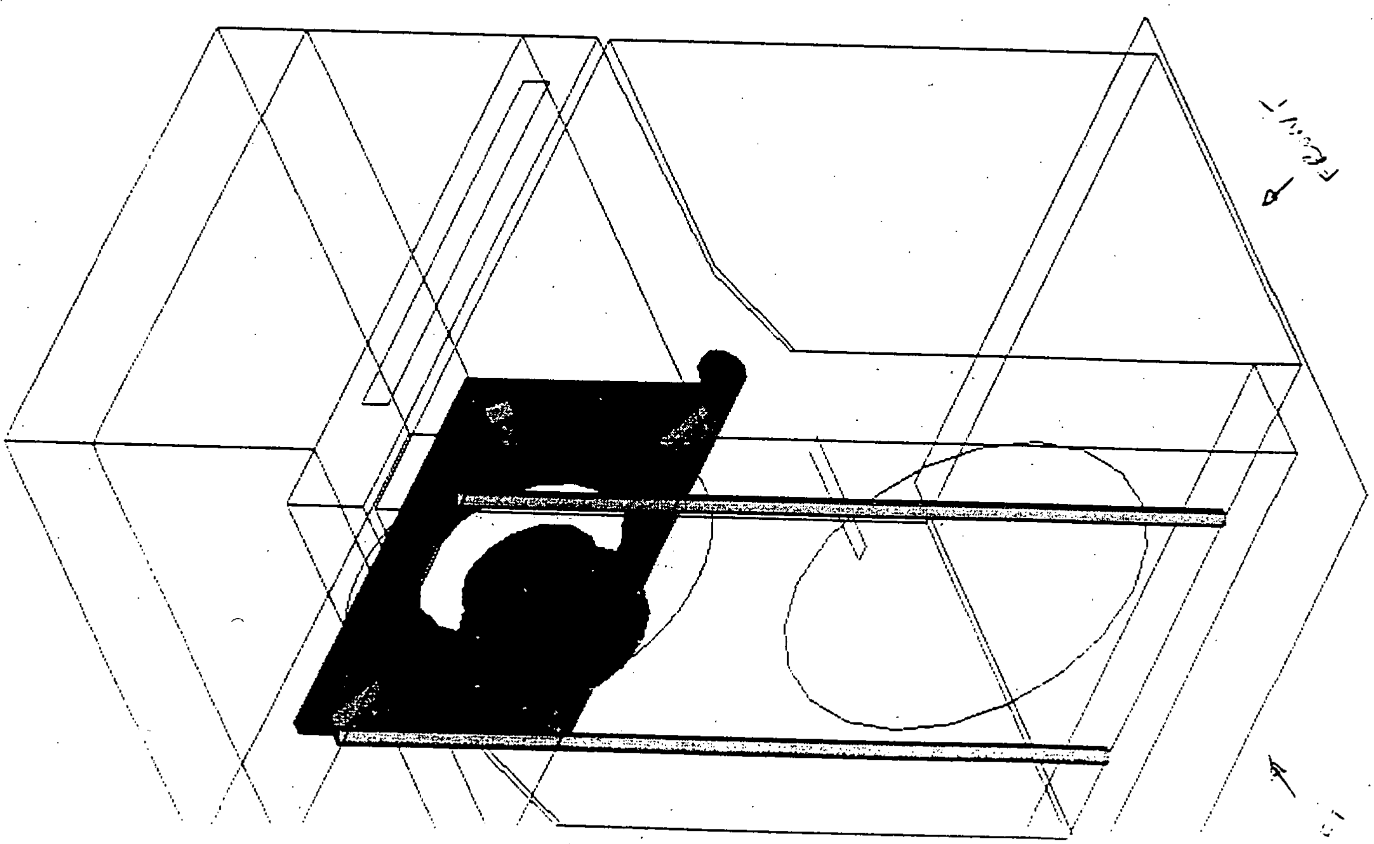
A26



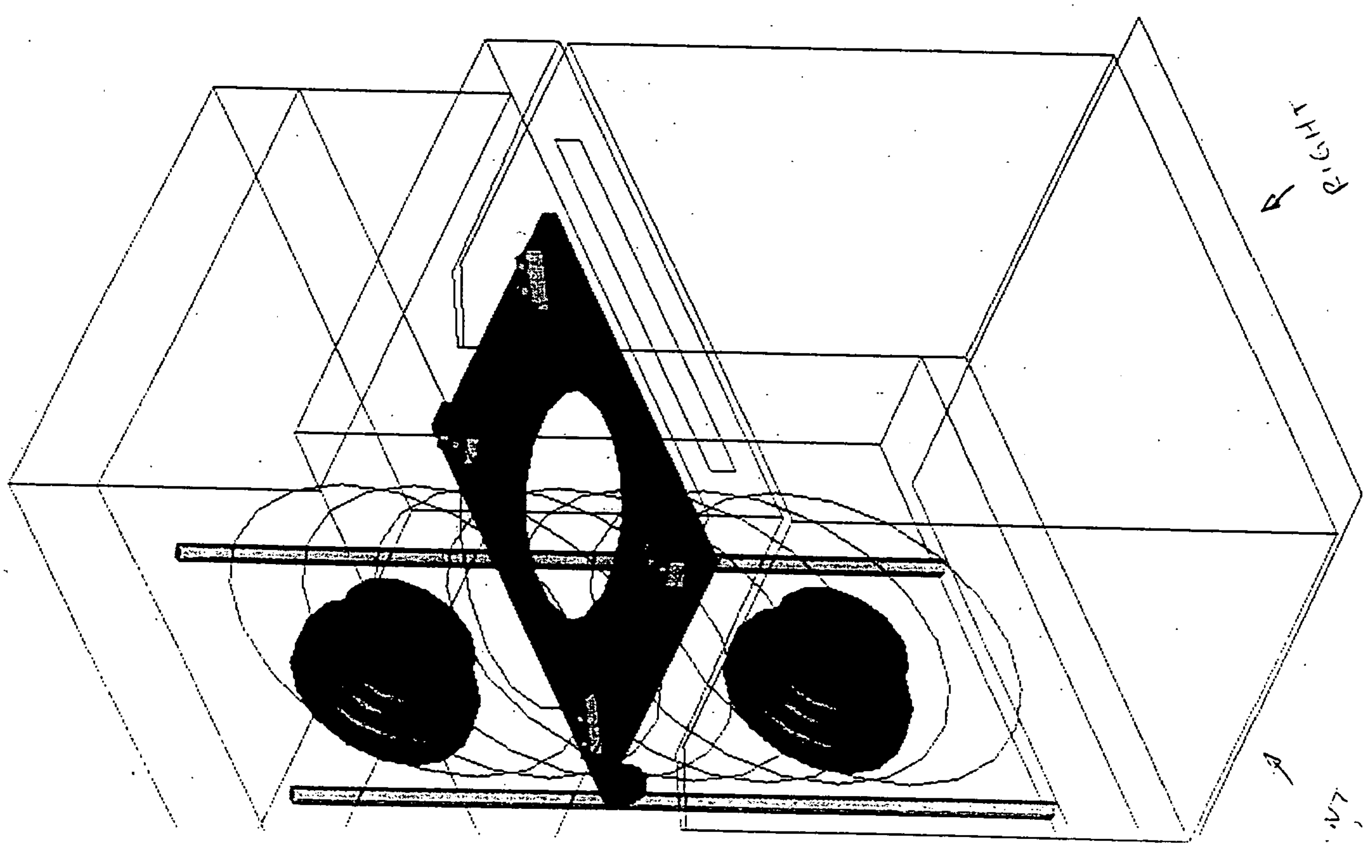
A27



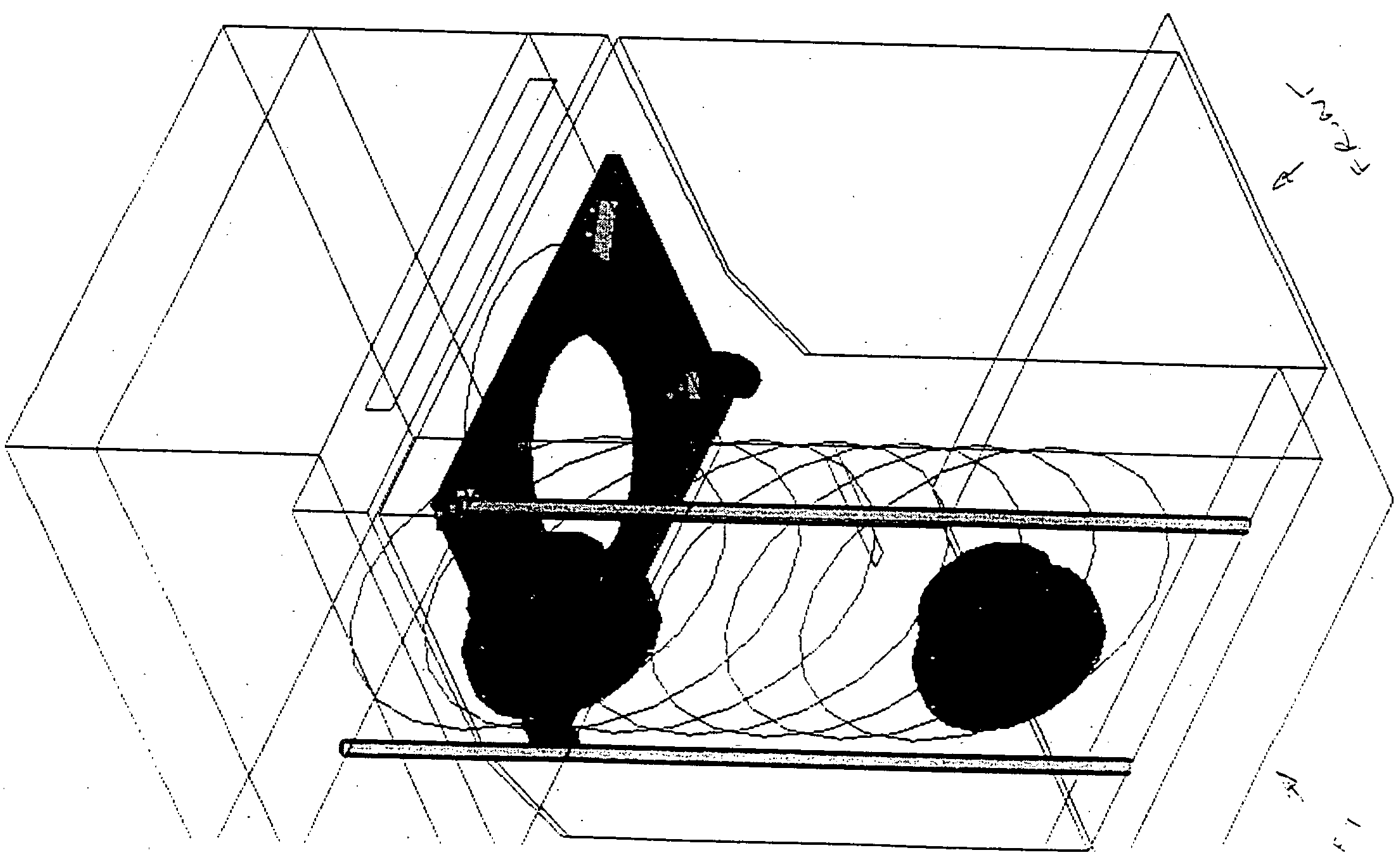
A28

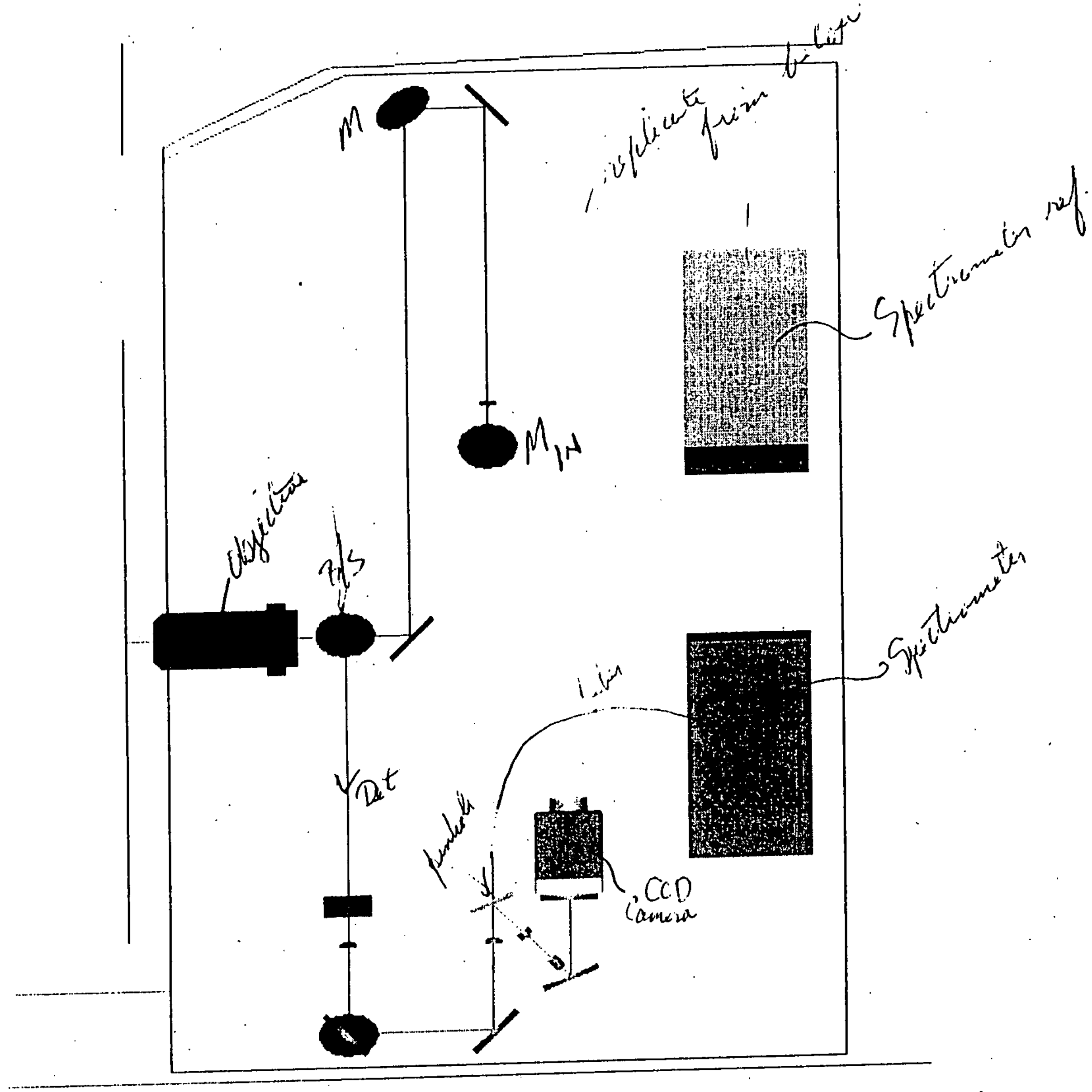


A29



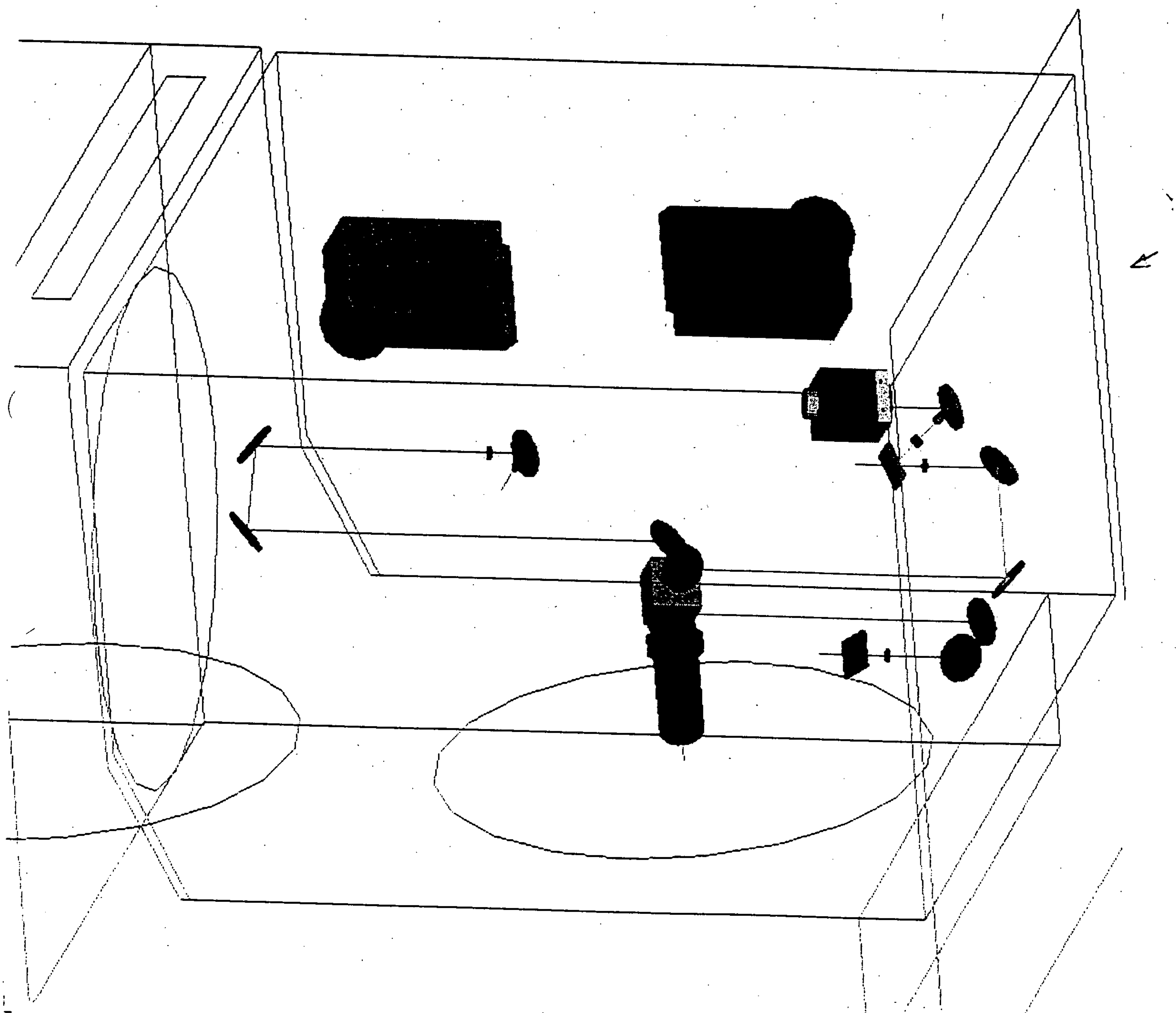
A30


FRONT

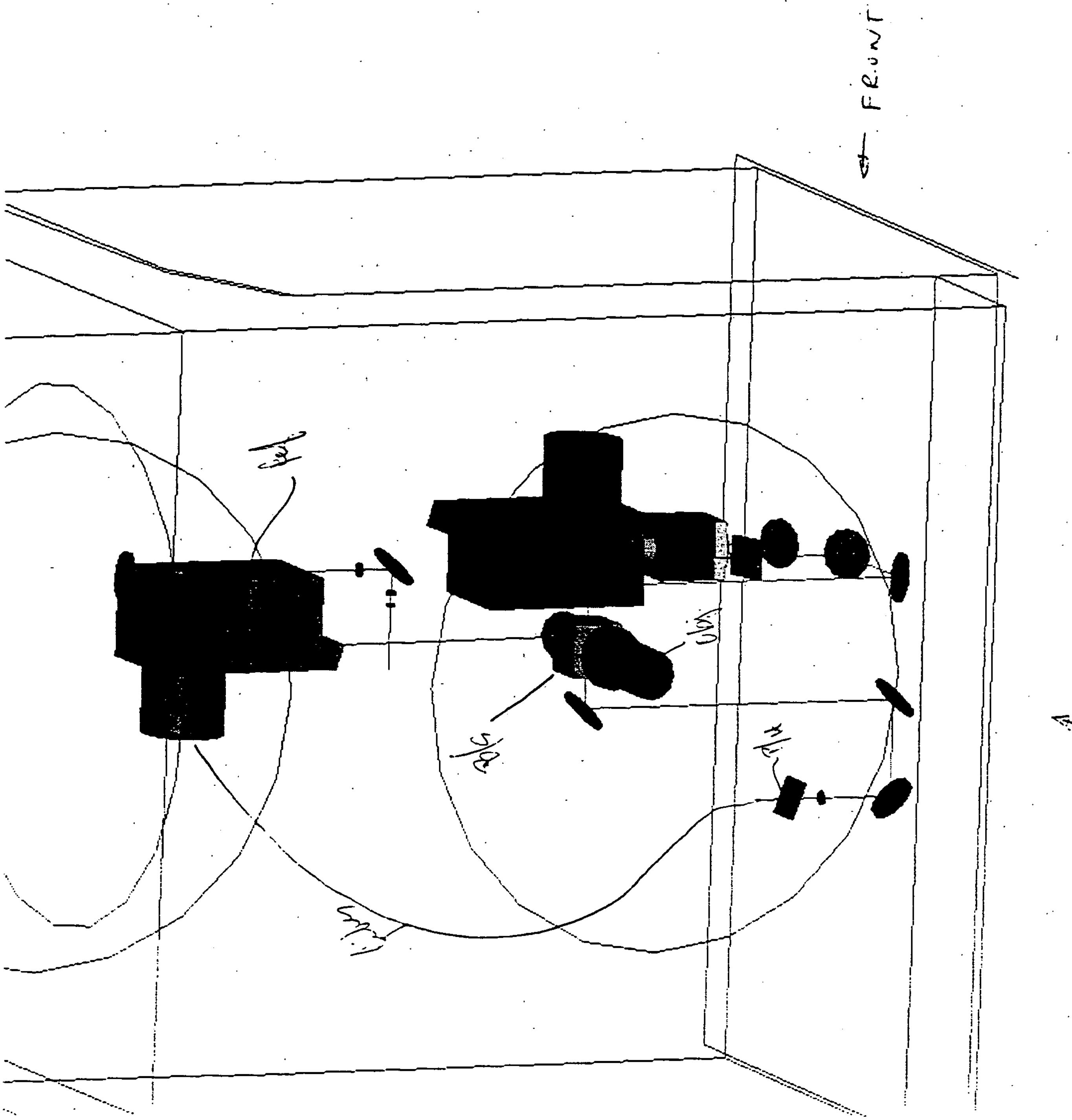


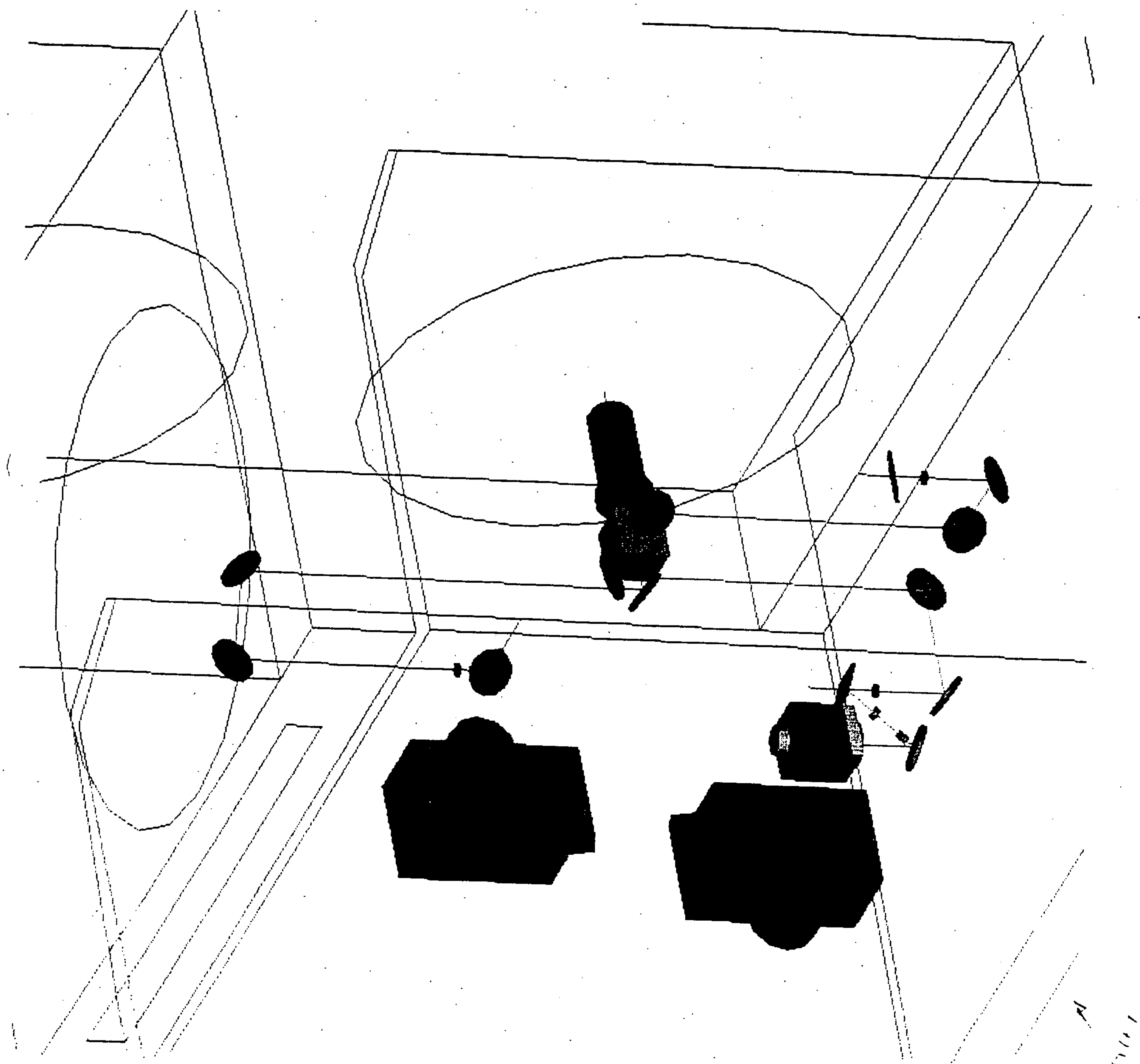
Path length ~~same~~
obj. moves w/ T

Front View



A23


FRONT
LEFT



A35

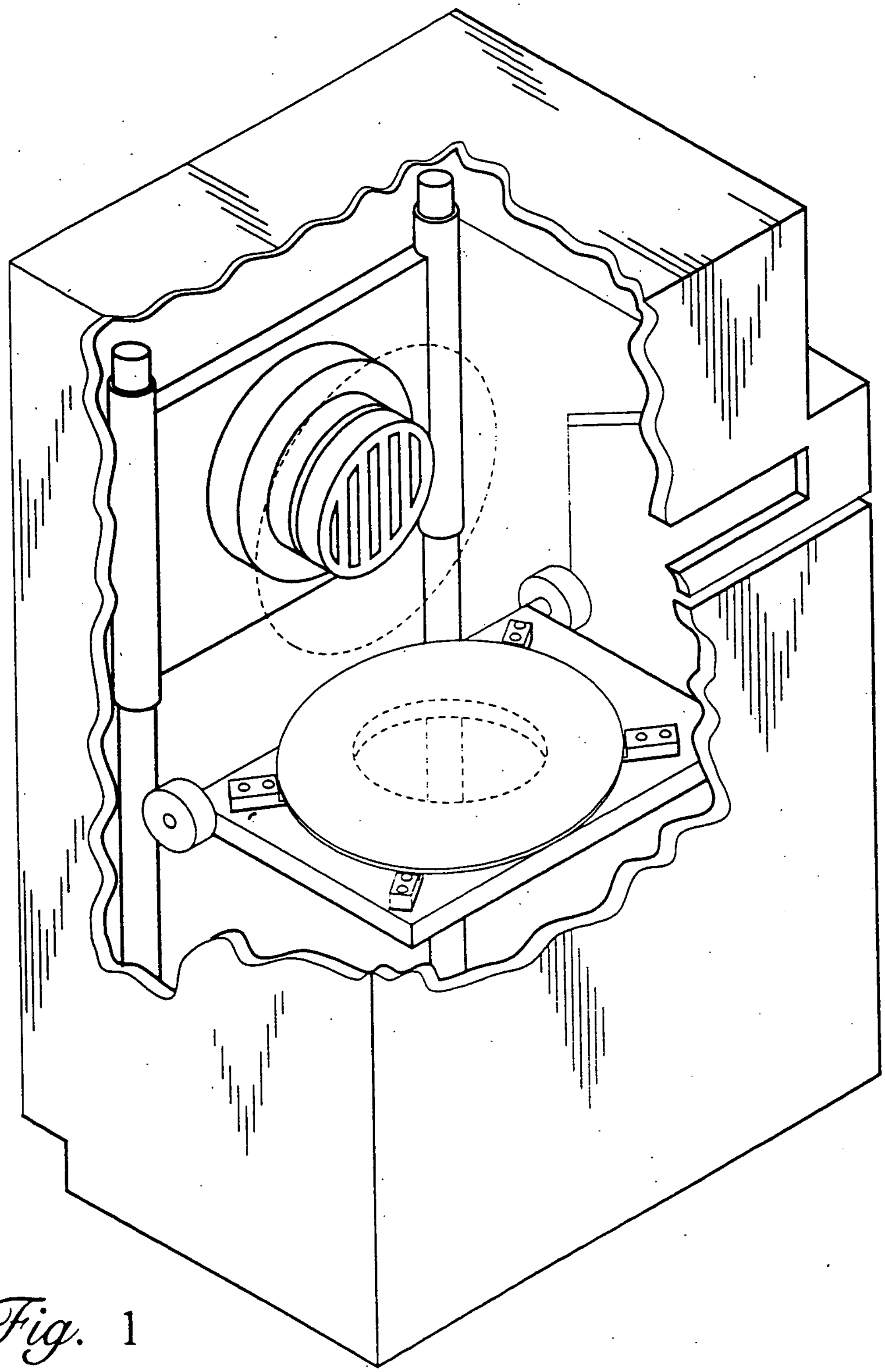


Fig. 1

A3 /

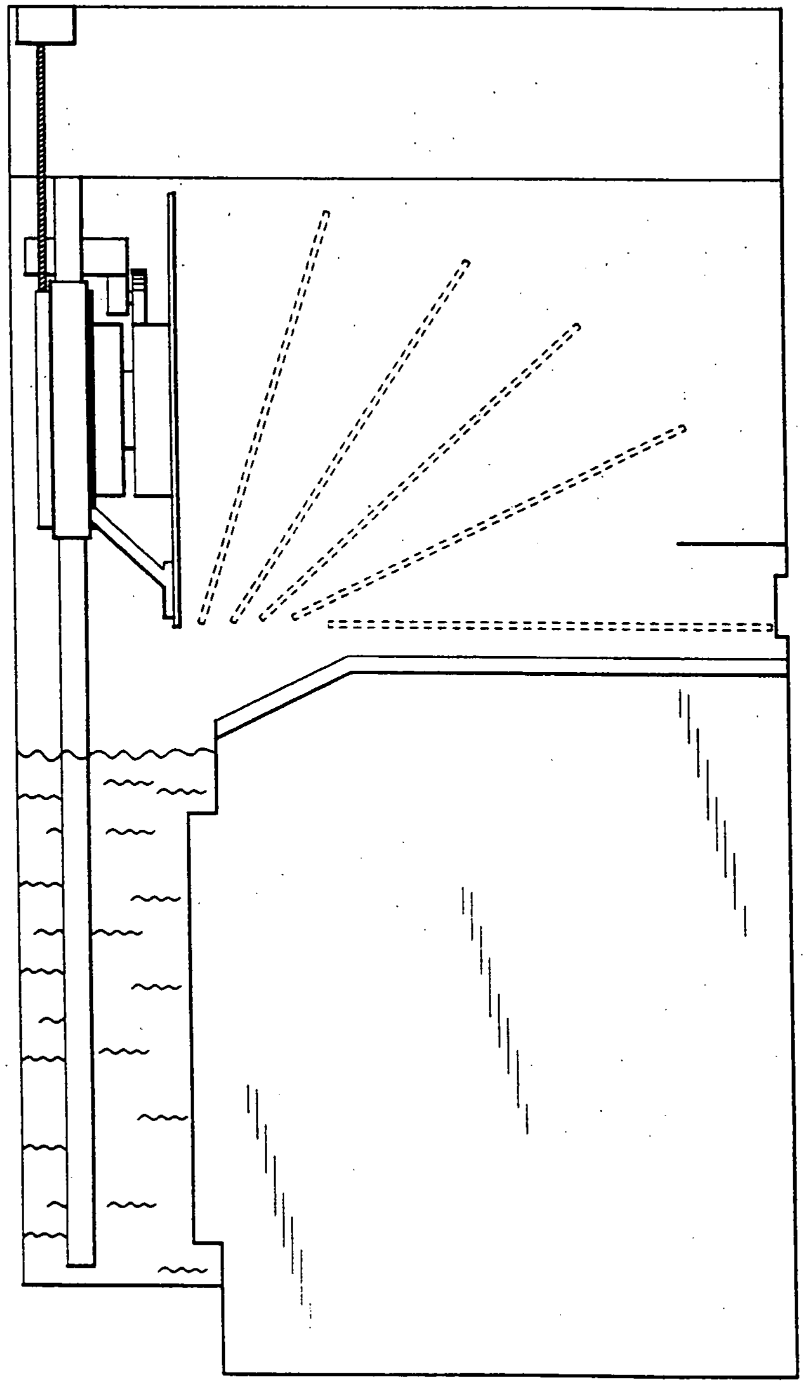


Fig. 2

A37

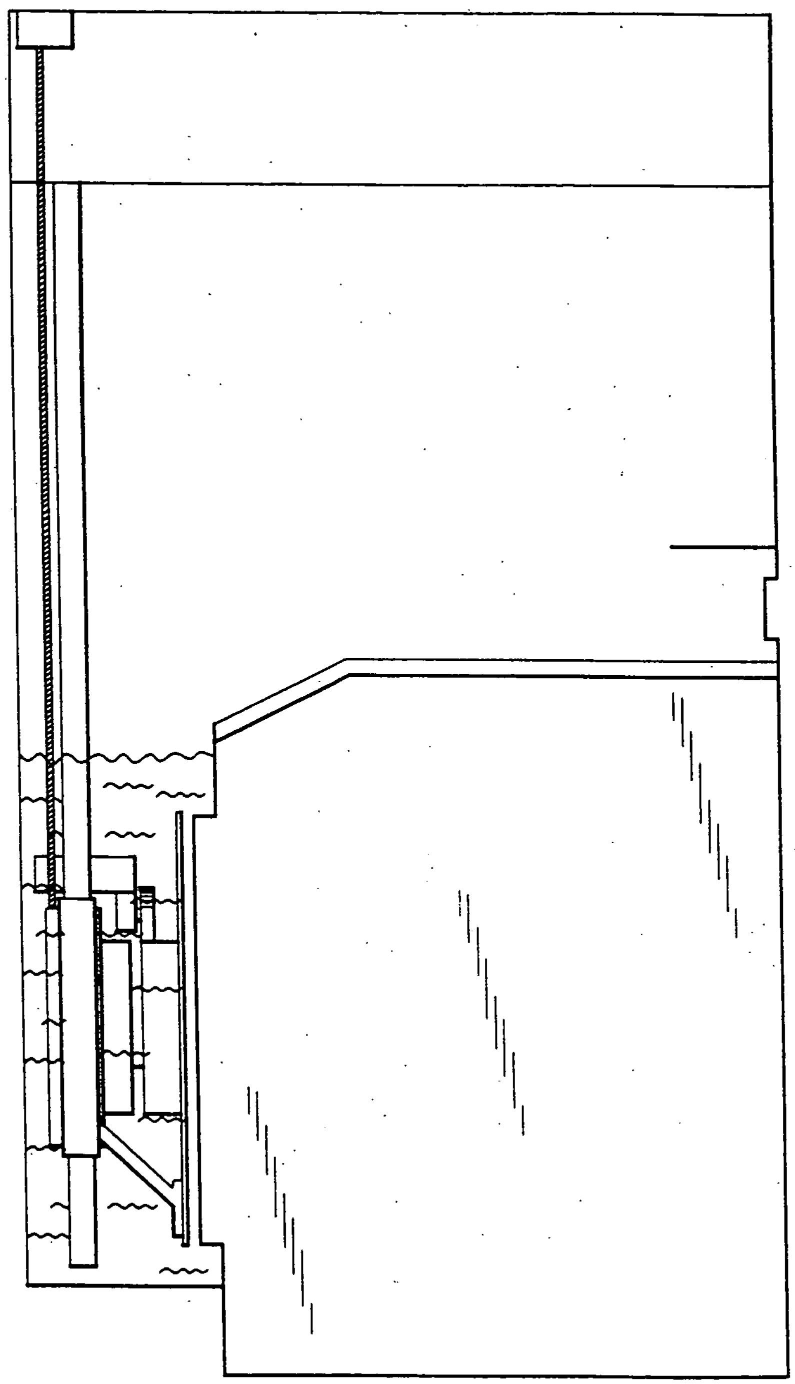


Fig. 3

A28

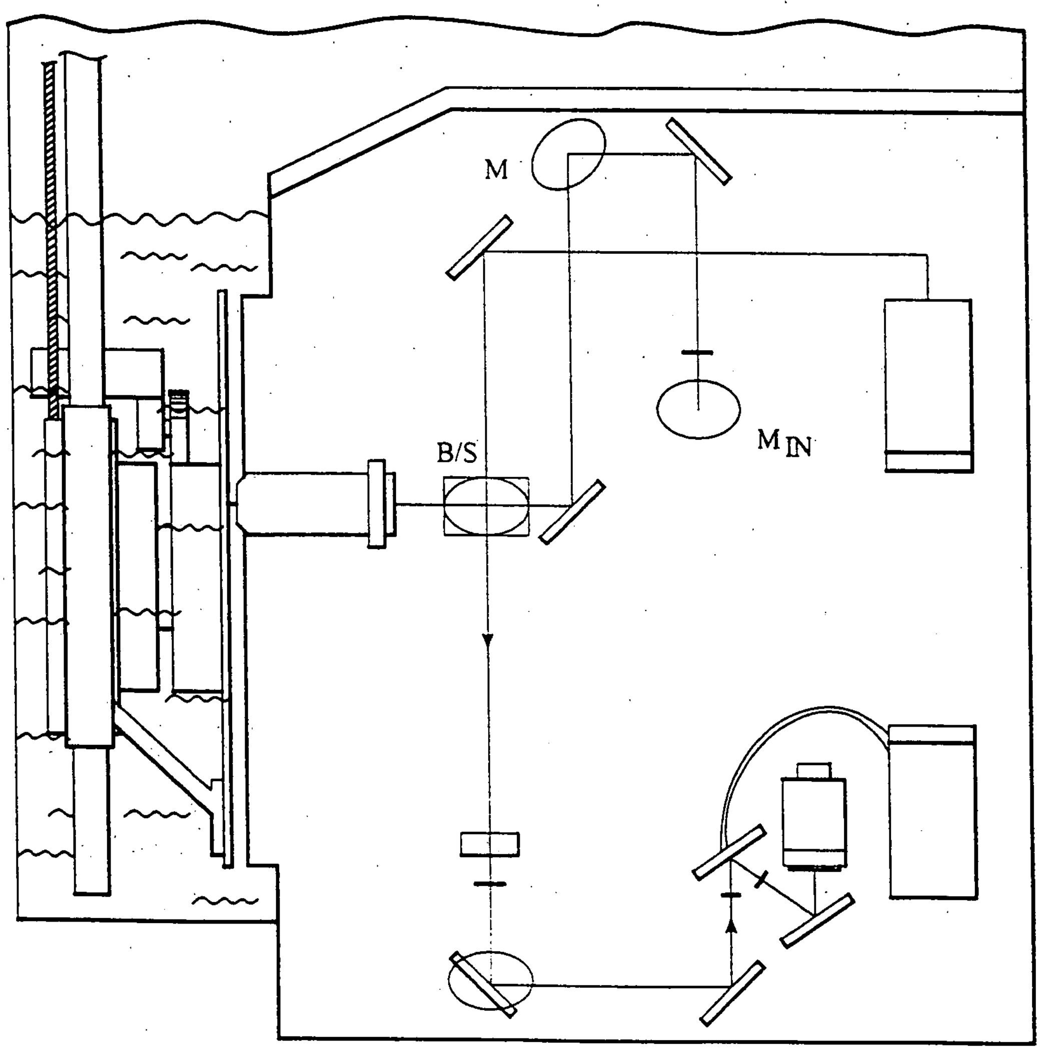


Fig. 4

A39

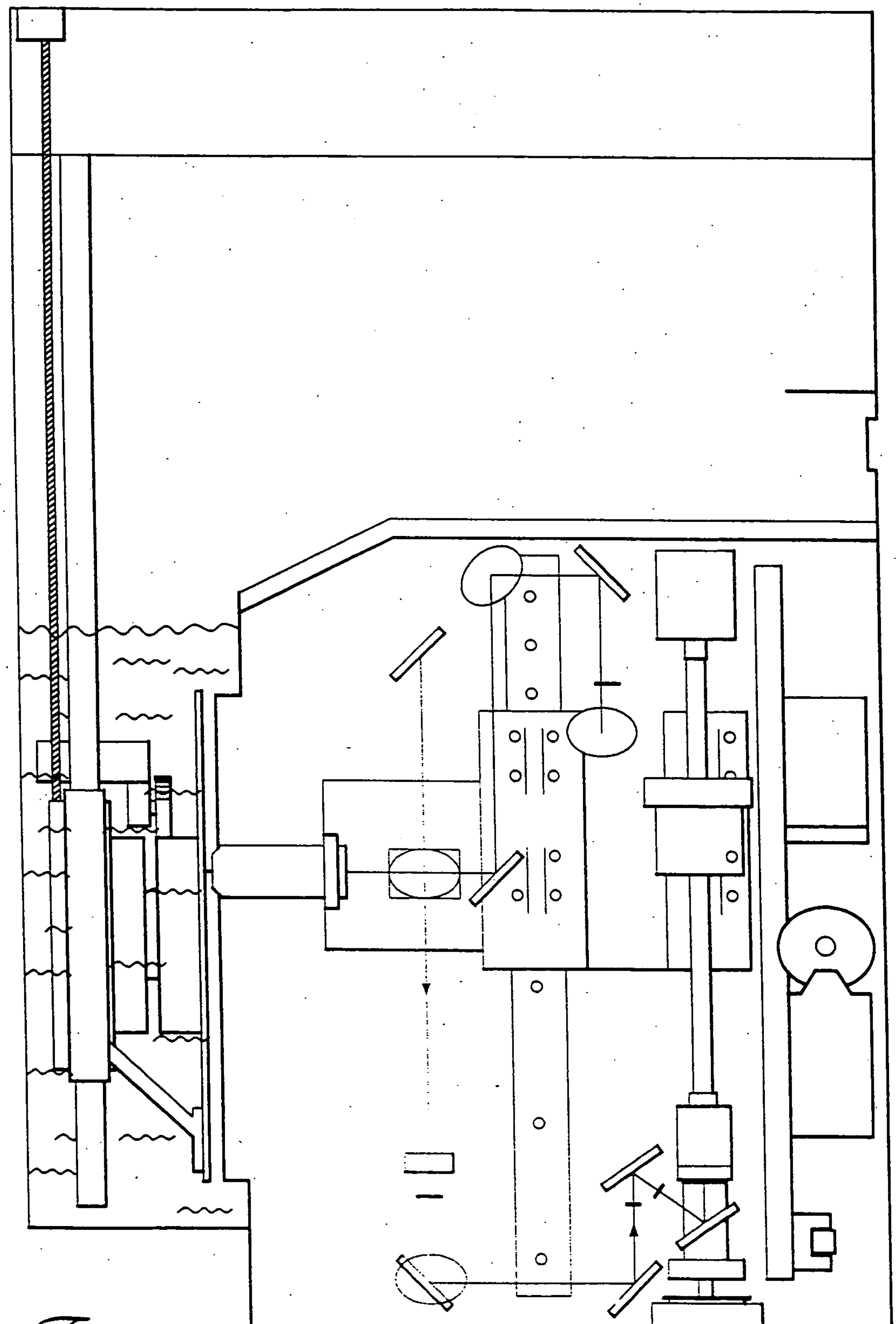
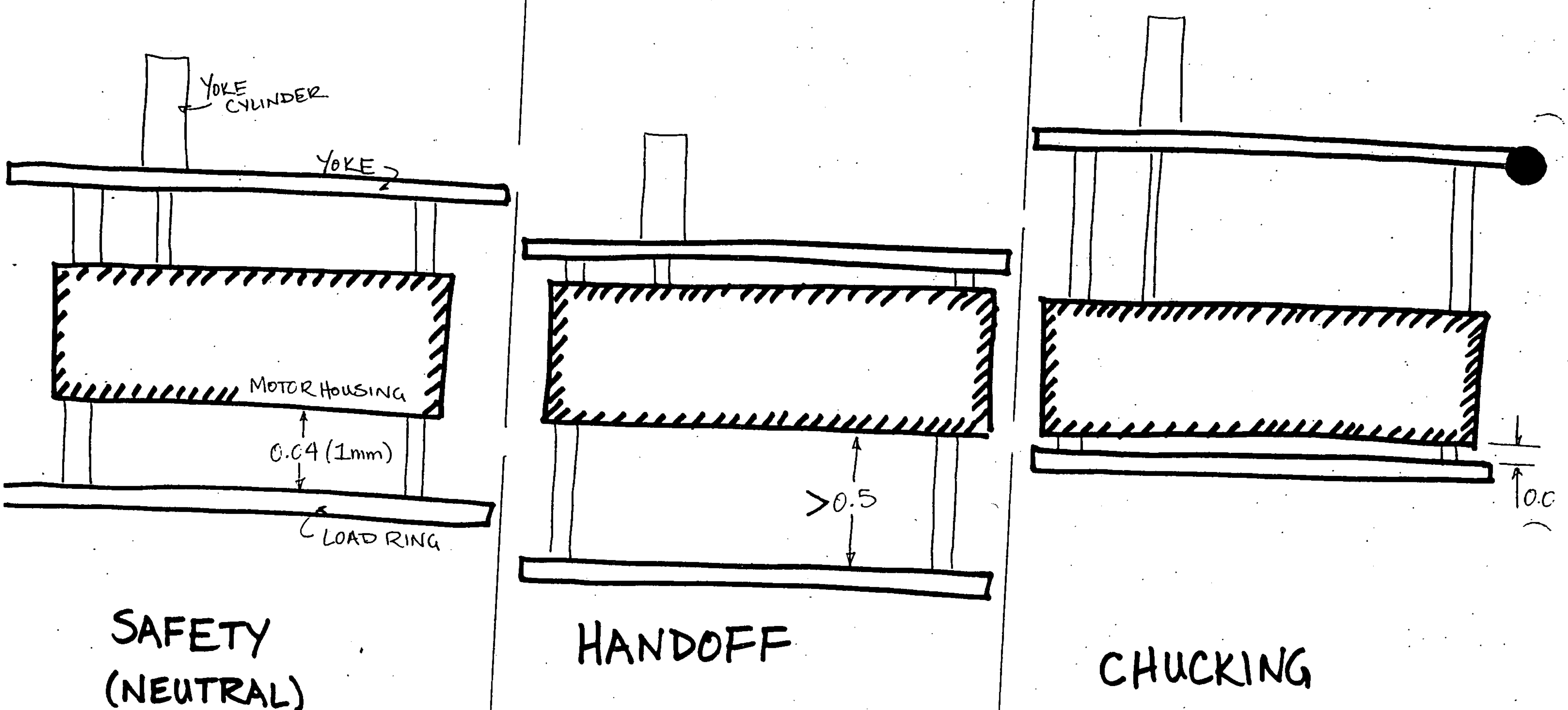


Fig. 5

A 40

LOAD RING

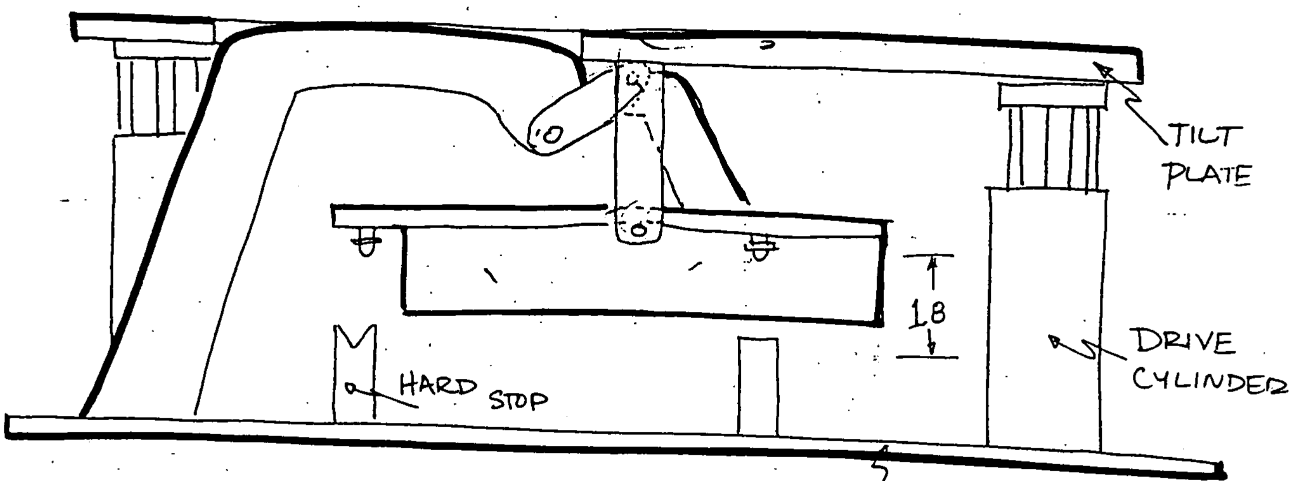


A41

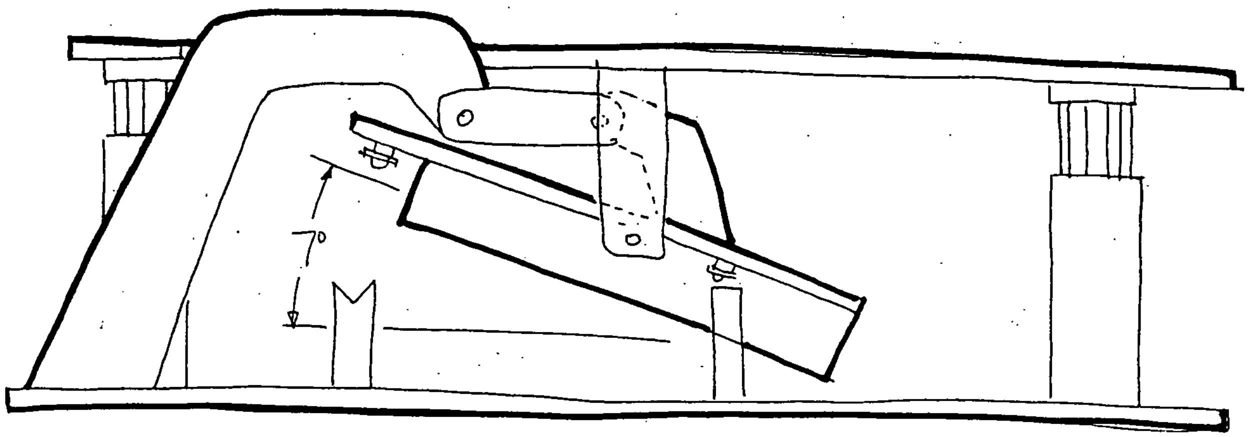
HK OCT 14 1998

TILT PLATE HARD STOPS

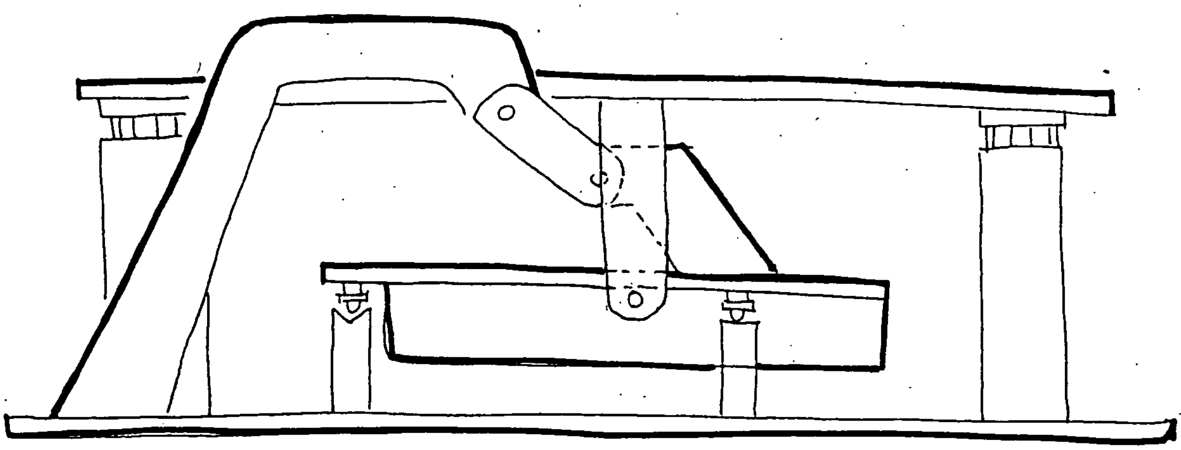
1



TOP



~7°

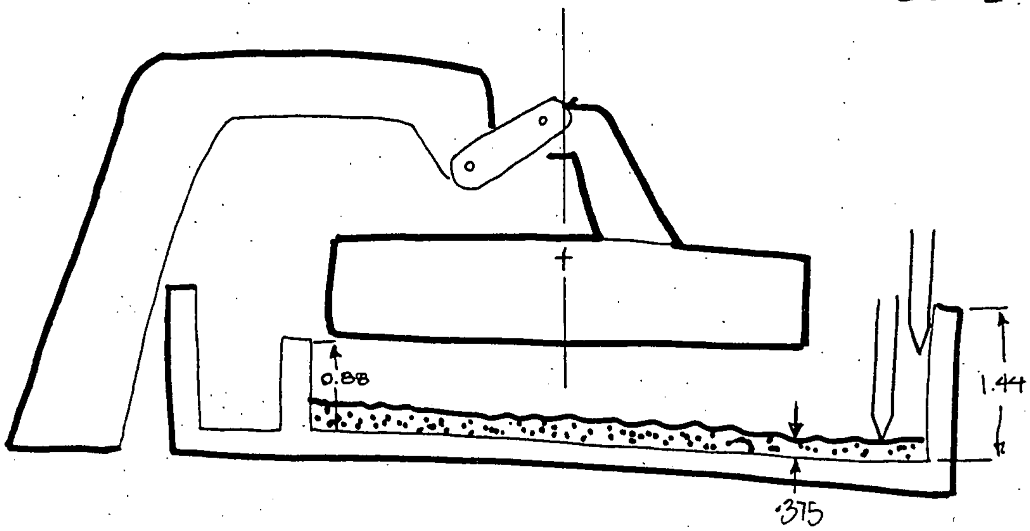


p 42

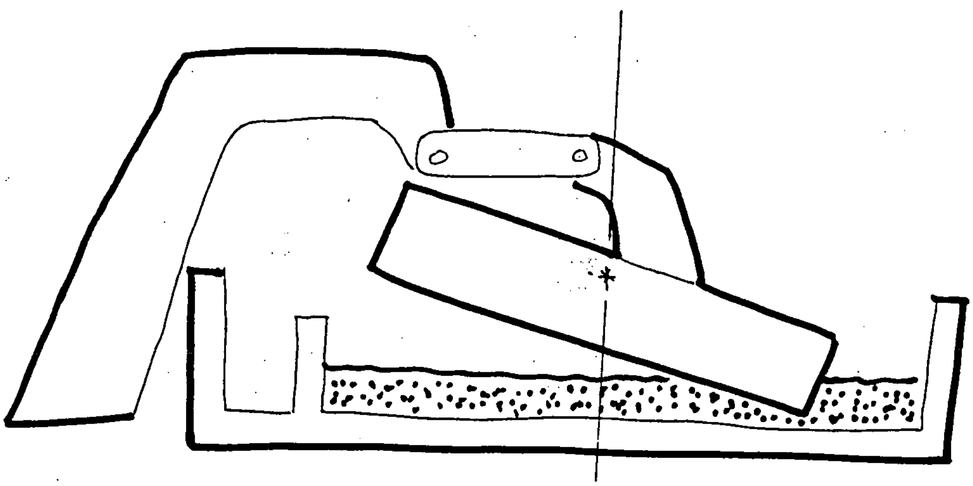
BOTTOM

WATER LEVEL

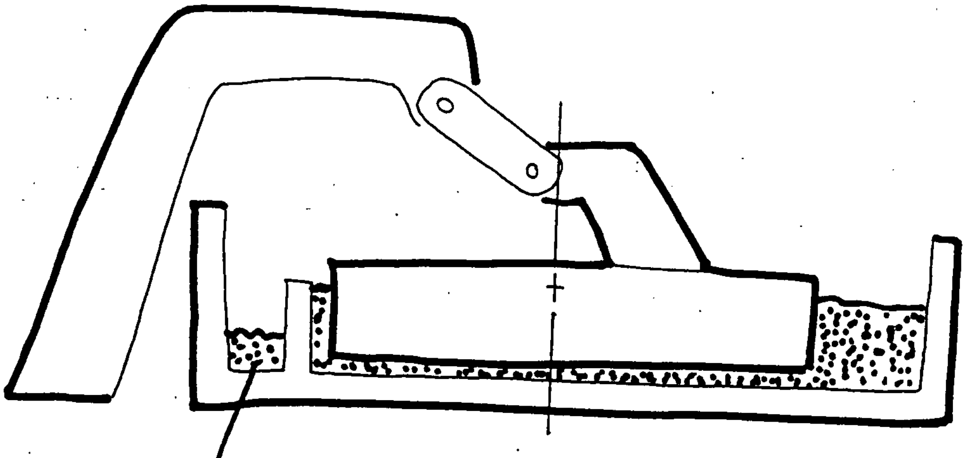
TOTAL TRAVEL = 1.8 in



TOP



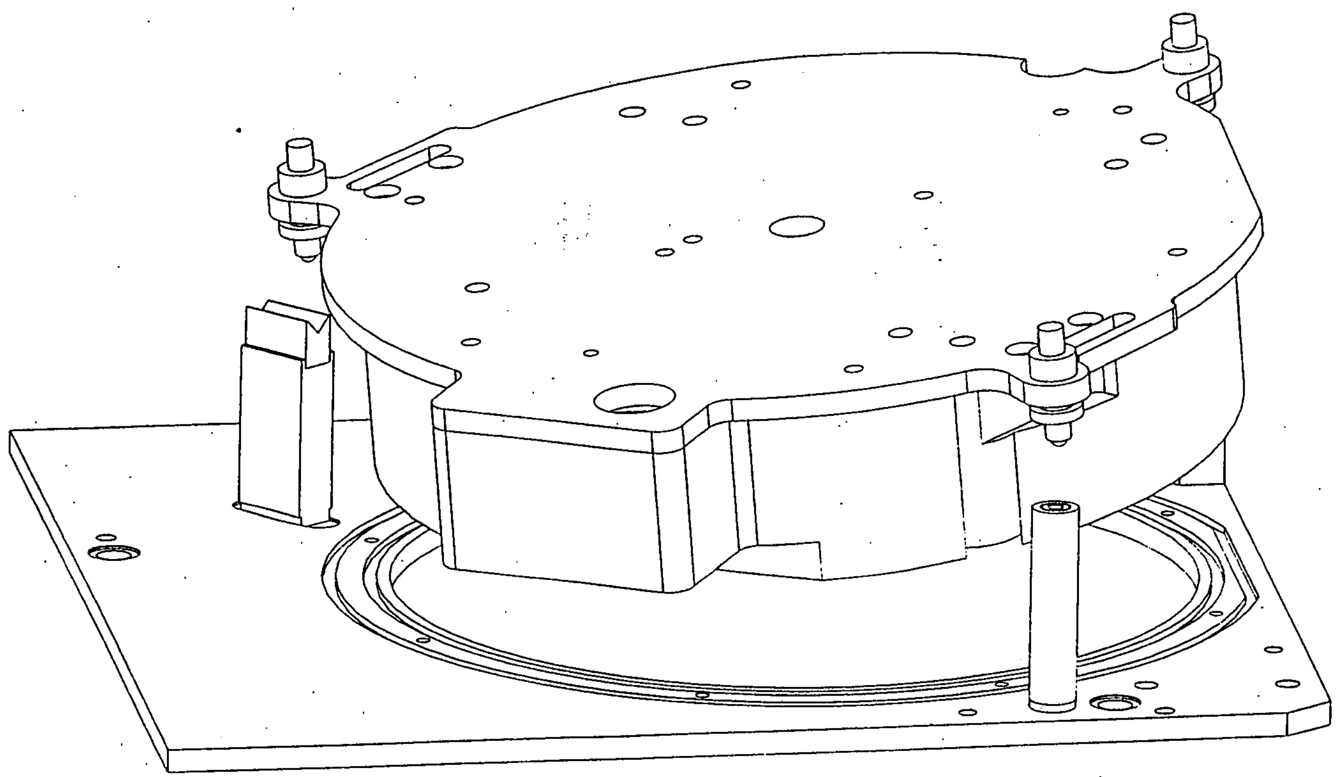
7°



BOTTOM

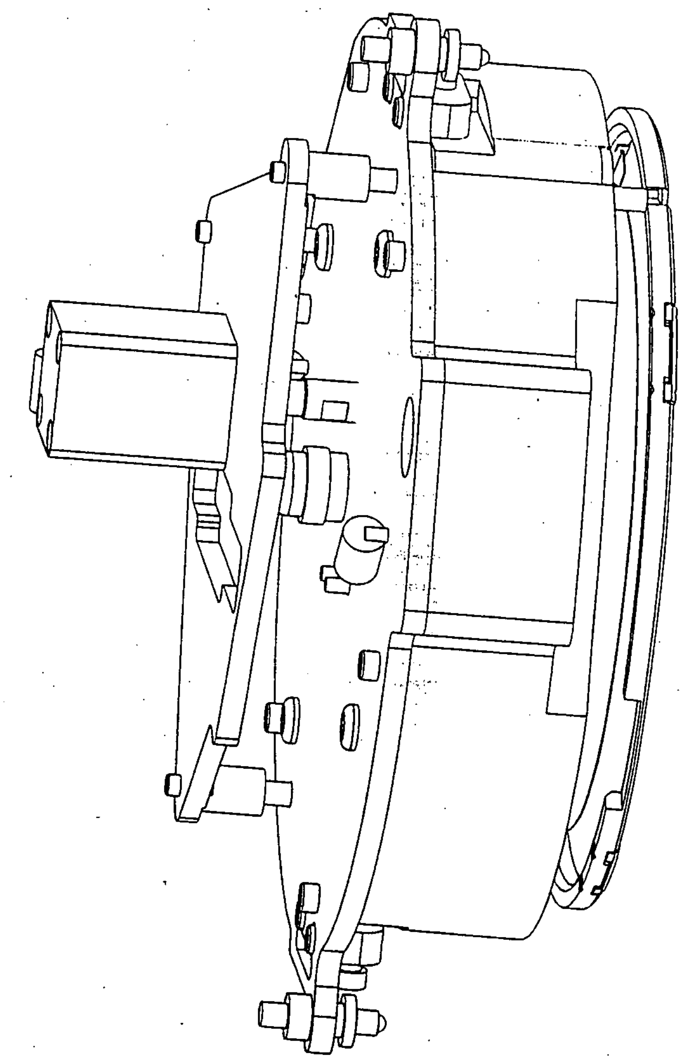
TO DRAIN

A43

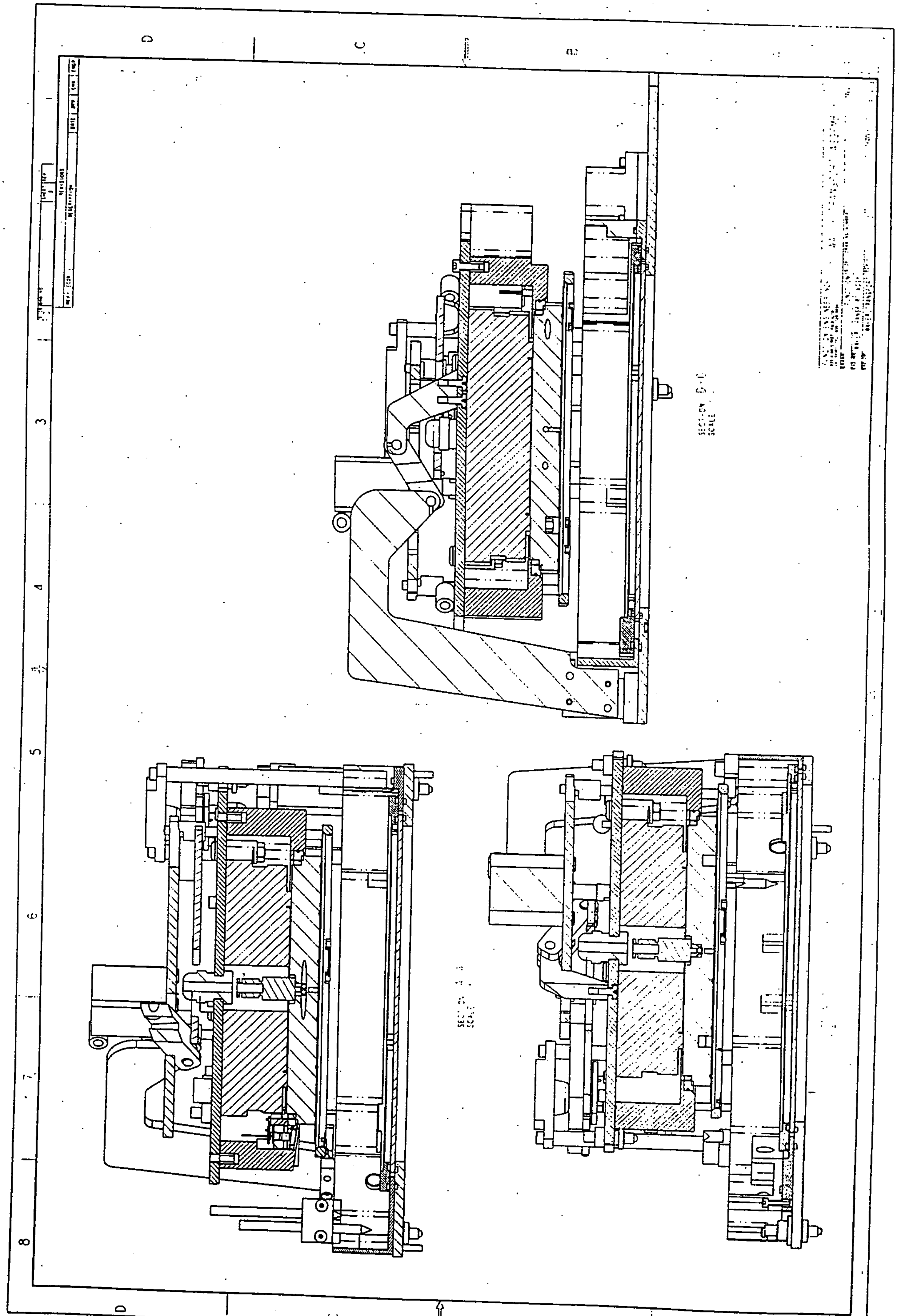


SIMPLIFIED PEP:HARD_STOP

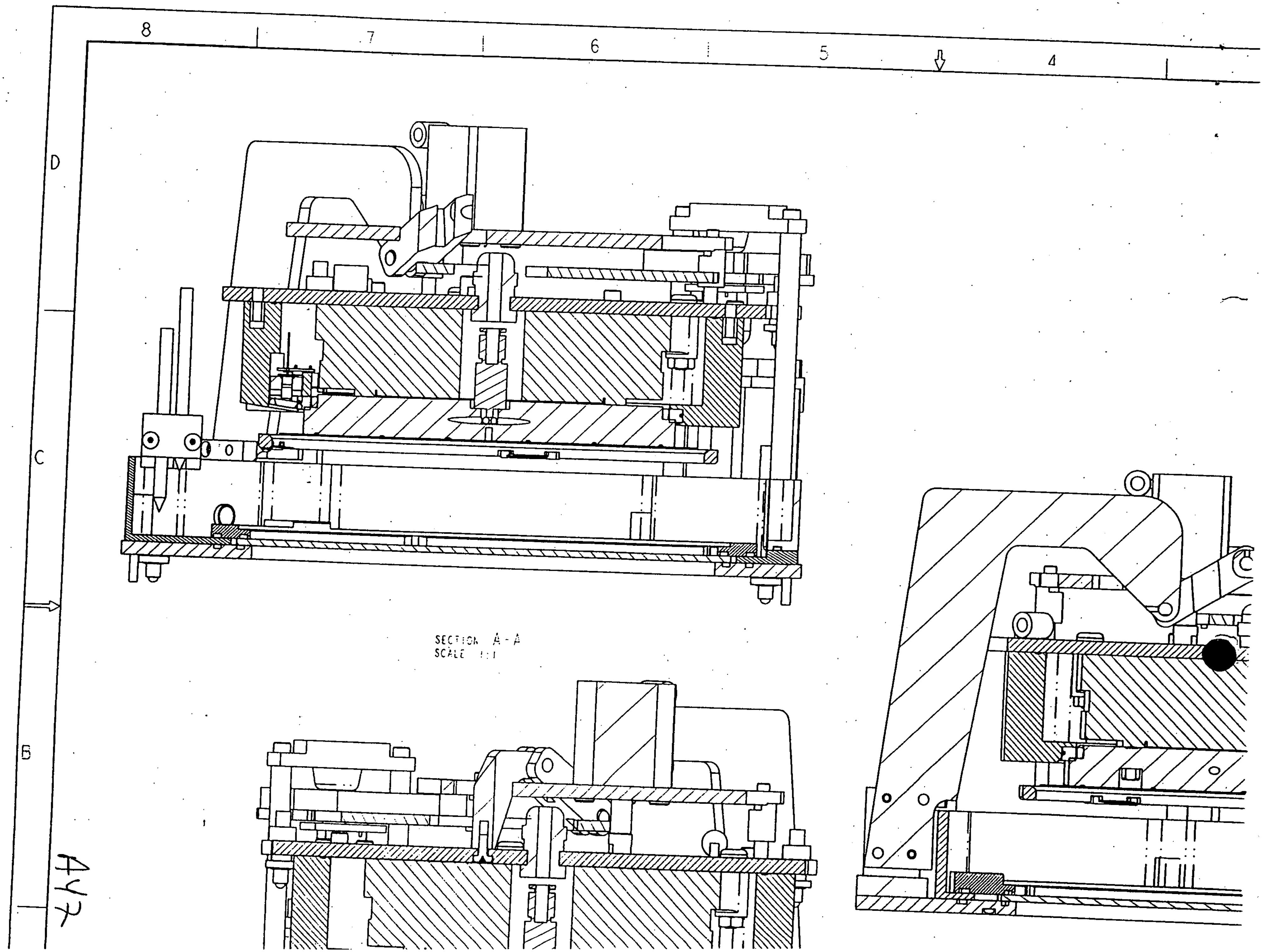
A 44

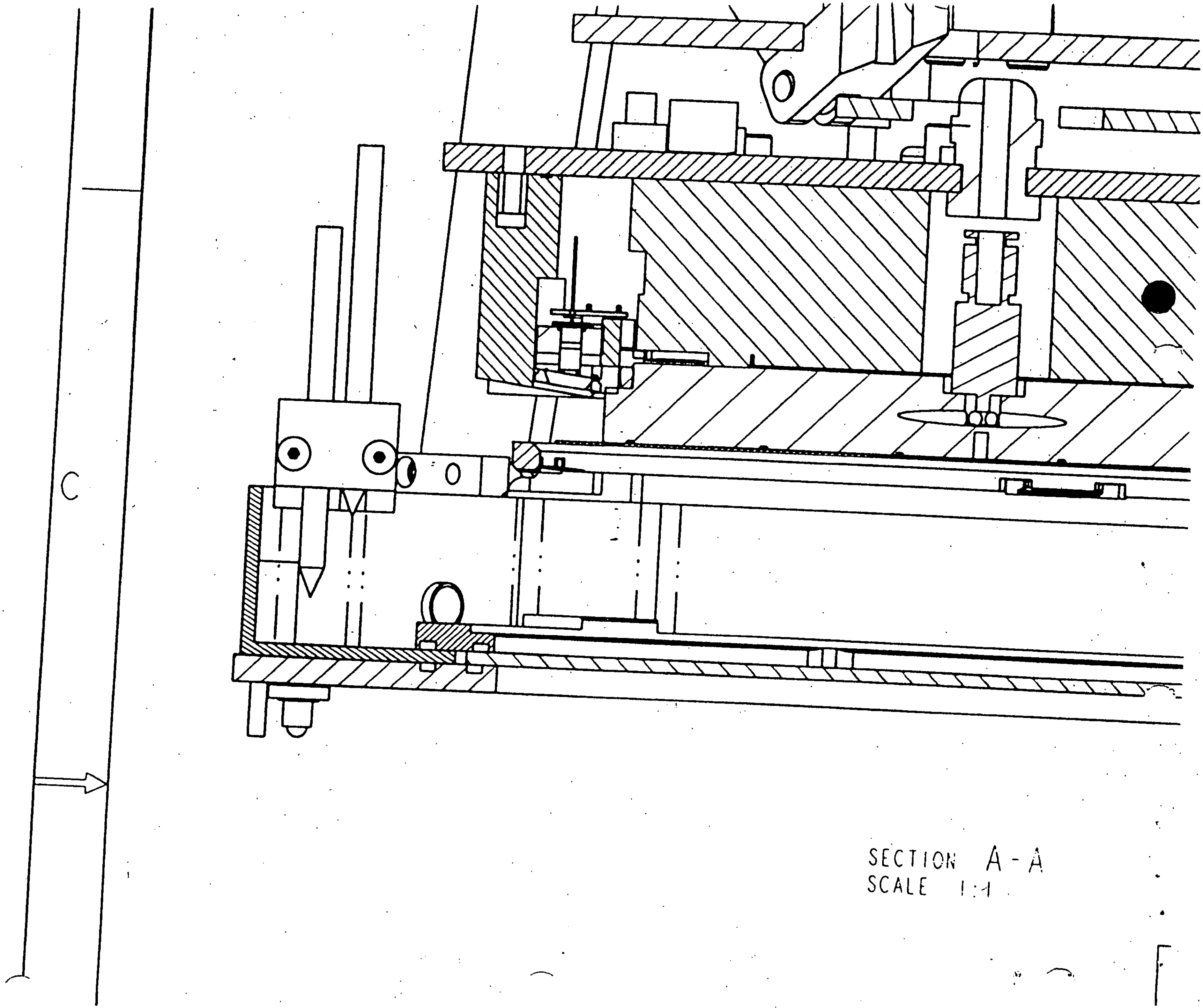


A 45



AY(


8
7
6
5
4
D
C
B
SECTION A-A
SCALE 1:1
A47



A48

Direct-Drive ead Screw 28 Jan

Mount the components of a motor directly onto the lead screw shaft. i.e. As for a DC brushless motor, mount the magnetic hub directly onto lead screw and house stator windings stationary around hub.

Exciting to stator windings electrially turns magnetic hub, and therefore lead screw.

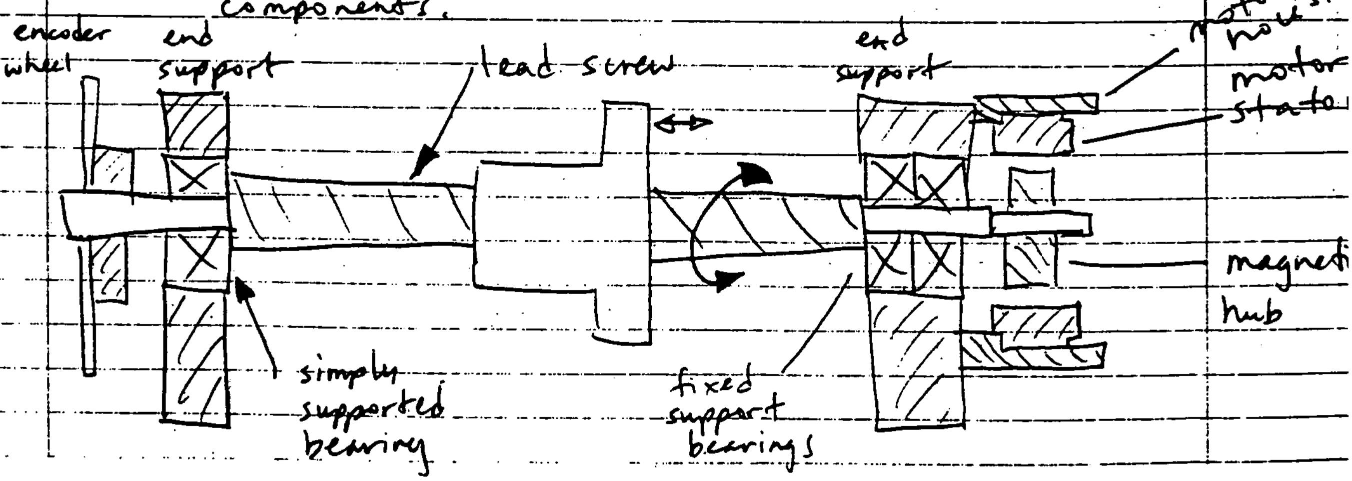
Key Advantages

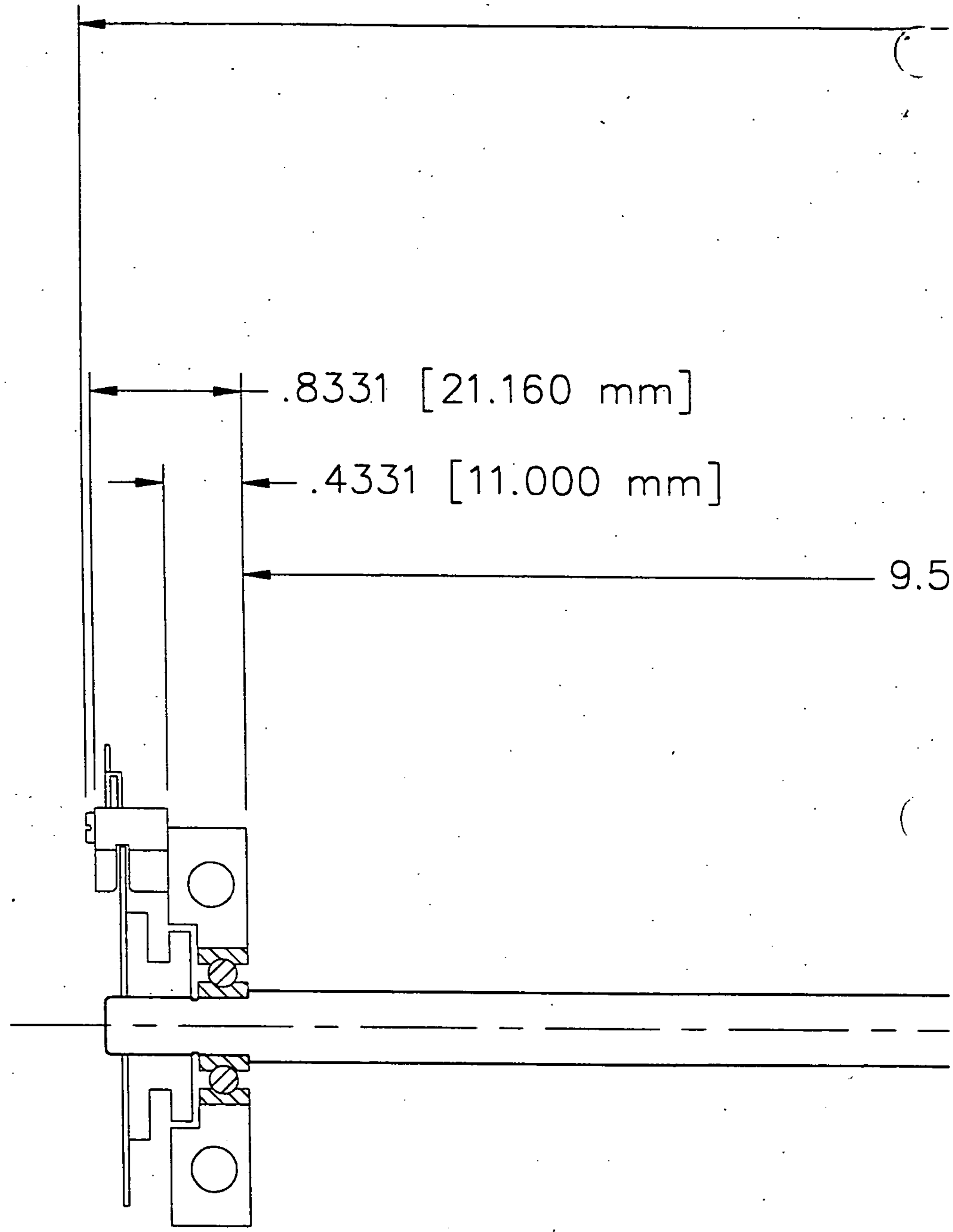
1) - compact length. ~~There are~~ No axial length needed for motor bearings, coupling, and motor housing endbells.

2) - stiffness. Since there is no coupling between the motor and the leadscrew, torsional wind up of the coupling is eliminated.

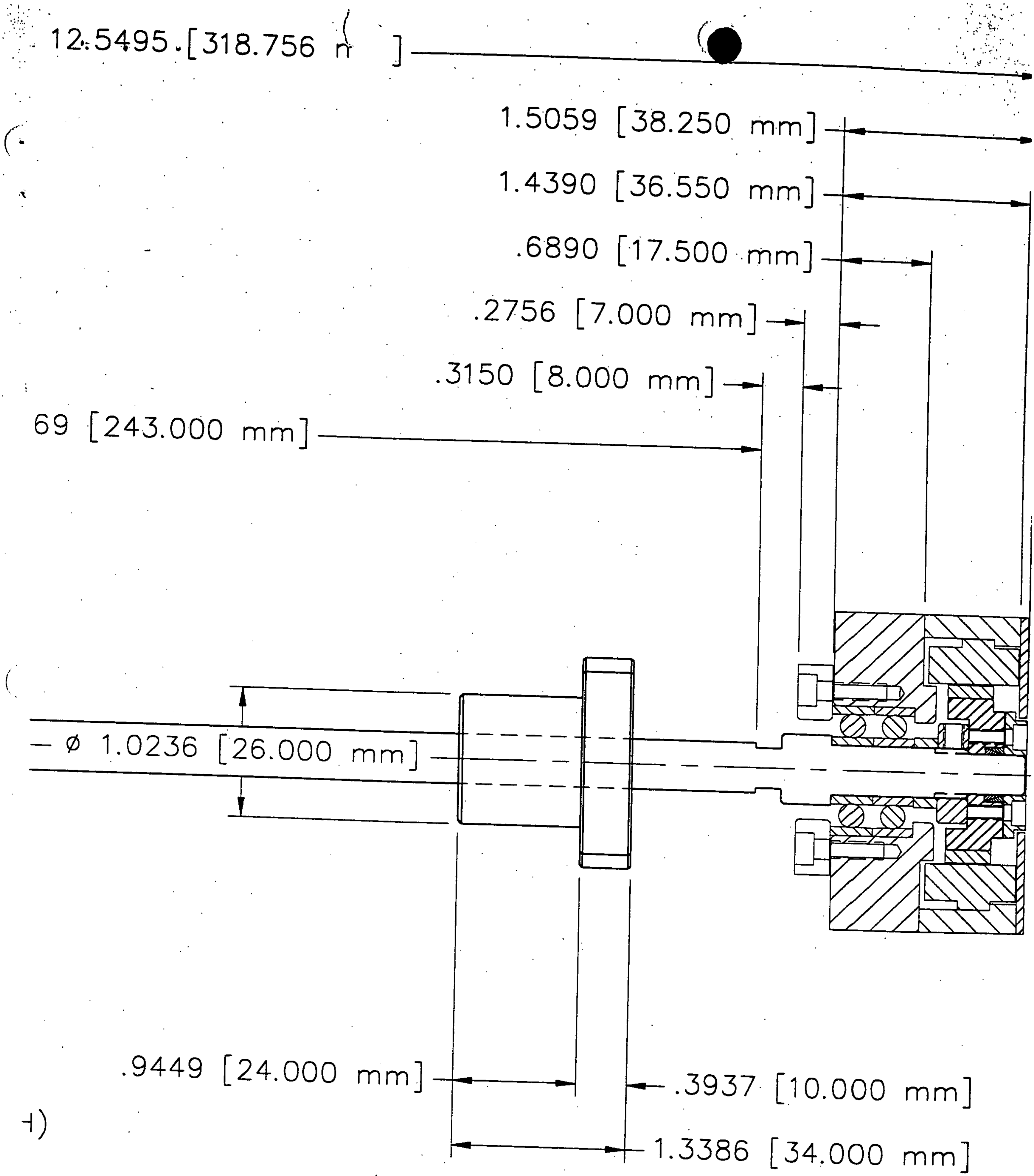
the torsional windup ~~will~~ can either cause position error of the lead screw or oscillations in the servo loop.

3) - alignment. Since there is no coupling between the motor and lead screw, axial alignment of the two shafts are non-existent. otherwise, this may lead to uneven loading on bearings (side-loads) which affects servoing and wearing of components.





REQUIRED TRAVEL: 200+4+10 = 214MM = 8.425"
(WAFER SIZE + LOAD TOLERANCE + HARD STOPS)
ACHIEVABLE TRAVEL: 243+5−34 = 214MM = 8.425"
(THREADED LENGTH + 5MM NUT CLEARANCE − NUT LEN
FRAMELESS MOTOR: 2.138 OD X 1.200 ID X 0.75 W
BALL SCREW: BASED ON THK: BNK1004−2.5RRG0+380LC3
DUPLEX: 10MM ID, 26MM OD, 8MM W (15°/16LB PRELOAD)
DEEP GROOVE: 8MM ID, 22MM OD, 7MM W
SHAFT ENCODER: 1000 LPR



12.5495 [318.756 m]
1.5059 [38.250 mm]
1.4390 [36.550 mm]
.6890 [17.500 mm]
.2756 [7.000 mm]
.3150 [8.000 mm]
69 [243.000 mm]
ø 1.0236 [26.000 mm]
.9449 [24.000 mm]
.3937 [10.000 mm]
1.3386 [34.000 mm]

6/18/98 EH

A5

PTO-103P
(Rev. 8-95) PROVISIONAL APPLICATION
FILING RECEIPT

UNITED STATES DEPARTMENT OF COMMERCE
Pat nt and Trad mark Office
ASSISTANT SECRETARY AND COMMISSIONER
OF PATENTS AND TRADEMARKS
Washington, D.C. 20231

APPLICATION NUMBER	FILING DATE	FIL FEE REC'D	ATTORNEY DOCKET NO.	DRWGS
60/125,462	03/22/99	$150.00	21964-703	21

PAUL DAVIS
WILSON SONSINI GOODRICH AND ROSATI
650 PAGE MILL ROAD
PALO ALTO CA 94304-1050

Receipt is acknowledged of this Provisional Application. This Provisional Application will not be examined for patentability. Be sure to provide the PROVISIONAL APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION when inquiring about this application. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. If an error is noted on this Filing Receipt, please write to Box Provisional Application within 10 days of receipt. Please provide a copy of the Provisional Application Filing Receipt with the changes noted thereon. This Provisional Application will automatically be abandoned twelve (12) months after its filing date and will not be subject to revival to restore it to pending status beyond a date which is after twelve (12) months from its filing date.

Applicant(s) FRED E. STANKE, CUPERTINO, CA; CLINTON B. CARLISLE, UNION CITY, CA; HUNG PHAM, SAN JOSE, CA; EDRIC TONG, SUNNYVALE, CA; ROBERT HAMSTRA, SAN JOSE, CA; DOUGLAS E. RUTH, SUNNYVALE, CA; JAMES CAHILL, SAN JOSE, CA; MICHAEL WEBER, SUNNYVALE, CA; ELLIOT BURKE, SANTA BARBARA, CA.

IF REQUIRED, FOREIGN FILING LICENSE GRANTED 04/14/99
TITLE
METHOD AND APPARATUS FOR WAFER METROLOGY

DATA ENTRY BY: YON, LOWUAN TEAM: 05 DATE: 04/14/99

PROVISIONAL APPLICATION COVER SHEET

This is a request [redacted]g a PROVISIONAL APPLICATION under 37 CFR [redacted]c)

1.53(b2)

Express Mail label number EM089311307US Date of Deposit March 22, 1999
I hereby certify that this paper or fee is being deposited with the United States Postal Service
"Express Mail Post Office to Addressee" service under 37 CFR § 1.10
on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, DC 20231.

John O. Gilmore
Name of person signing

Signature

Docket Number	21964-703	Type a plus sign (+) inside this box →	+

INVENTOR(s)/APPLICANT(s)

LAST NAME	FIRST NAME	MIDDLE INITIAL	RESIDENCE (CITY AND EITHER STATE OR FOREIGN COUNTRY)
Stanke	Fred	E.	Cupertino, CA
Carlisle	Clinton	B.	Union City, CA

TITLE OF THE INVENTION (280 characters max)

Method and Apparatus for Wafer Metrology

CORRESPONDENCE ADDRESS

PAUL DAVIS
WILSON, SONSINI, GOODRICH & ROSATI
650 Page Mill Road
Palo Alto, California 94304-1050
Telephone: (650) 493-9300
Facsimile: (650) 493-6811

ENCLOSED APPLICATION PARTS (***check all that apply***)

☒ Specification	*Number of Pages* 82	☐ Small Entity Statement
☒ Drawing(s)	*Number of Sheets* 21	☐ Other (specify)________

METHOD OF PAYMENT (check one)

☐ A check or money order is enclosed to cover the Provisional filing fees. ☒ The Commissioner is hereby authorized to charge filing fees and credit Deposit Account Number: 23-2415, #21964-703	PROVISIONAL FILING FEE AMOUNT ($)	$150.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.
☐ Yes, the same of the U.S. Government agency and the Government contract number are: ________

Respectfully submitted,

SIGNATURE ________ Date: 03 /22 / 99

TYPED or PRINTED NAME John O. Gilmore REGISTRATION NO. ________ (if appropriate)

☒ Additional inventors are being named on separately numbered sheets attached hereto.

PROVISIONAL APPLICATION FILING ONLY

H:\PRIVATE\WPDOCS\PD\SENSYS\703.XMT

		Number			

INVENTOR(s)/APPLICANT(s)
SHEET 2

LAST NAME	FIRST NAME	MIDDLE INITIAL	RESIDENCE (CITY AND EITHER STATE OR FOREIGN COUNTRY)
Pham	Hung		San Jose, CA
Tong	Edric		Sunnyvale, CA
Hamstra	Robert		San Jose, CA
Ruth	Douglas	E.	Sunnyvale, CA
Cahill	James		San Jose, CA
Weber	Michael		Sunnyvale CA
Burke	Elliot		Santa Barbara, CA

H:\PRIVATE\WPDOCS\PD\SENSYS\703.XMT